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NIF Ignition Program: Progress and Planning

B. Hammel

June 5, 2006

33rd European Physical Society Conference on Plasma Physics
Rome, Italy
June 19, 2006 through June 23, 2006

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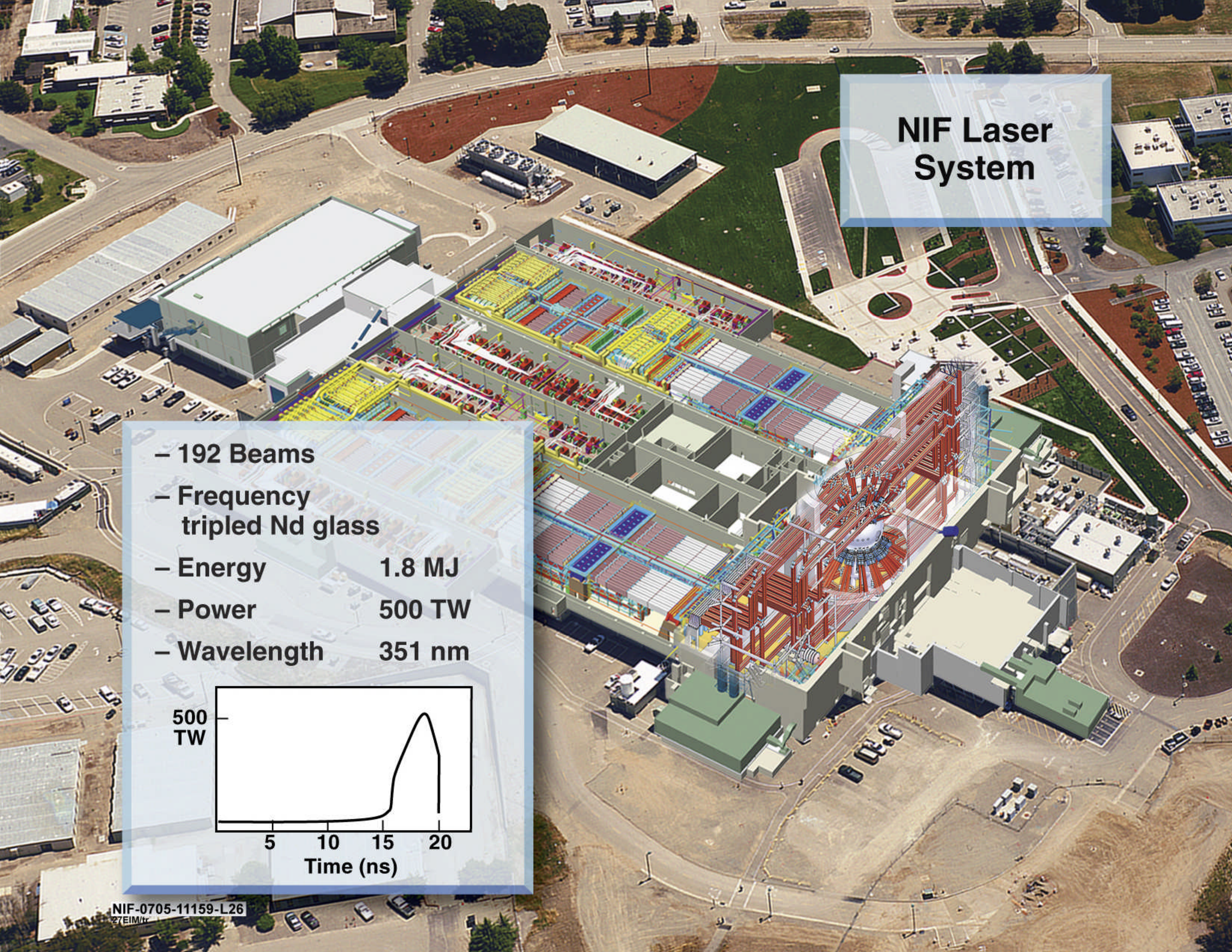
NIF Ignition Program: Progress and Planning

Presentation to
European Physical Society
June 23, 2006

Bruce Hammel
Lawrence Livermore National Laboratory

and
National Ignition Campaign Team


NIF Laser System
– 192 Beams
– Frequency tripled Nd glass
– Energy 1.8 MJ
– Power 500 TW
– Wavelength 351 nm
500 TW
5
10
15
20
Time (ns)
NIF-0705-11159-L26
27EIM/tr

First bundle tested
- **Meets all performance requirements**
- **Over 2 MJ equivalent in the UV**

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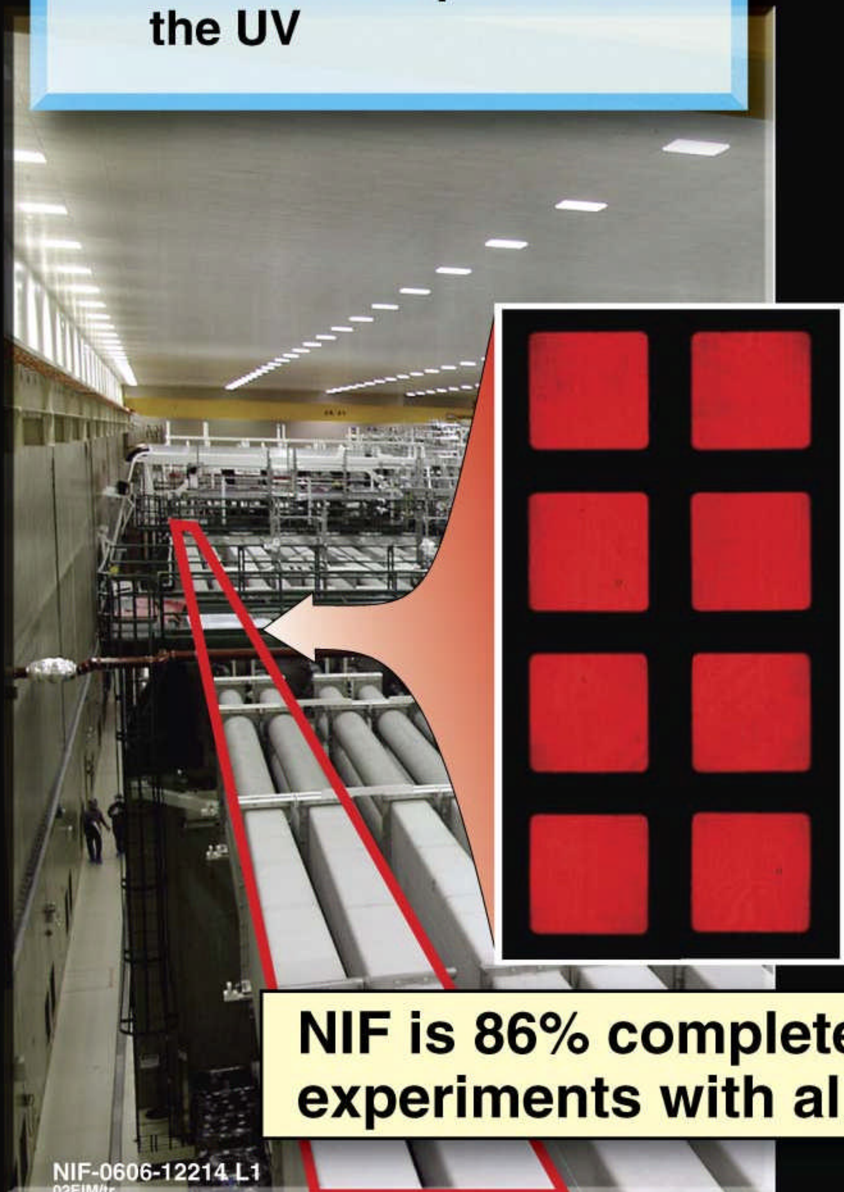
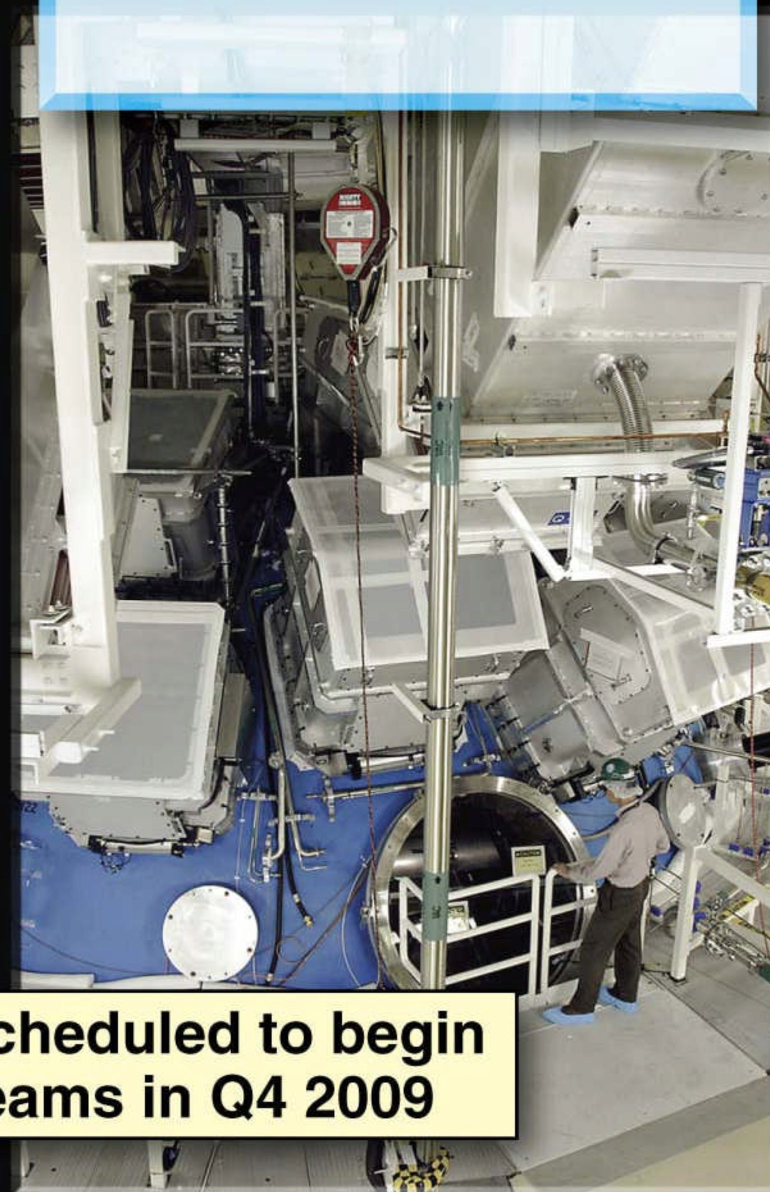
First experiments completed with one quad of beams





NIF is 86% complete and scheduled to begin experiments with all 192 beams in Q4 2009

NIF-0606-12214 L1
02EIM/tr

First bundle tested

- Meets all performance requirements
- Over 2 MJ equivalent in the UV

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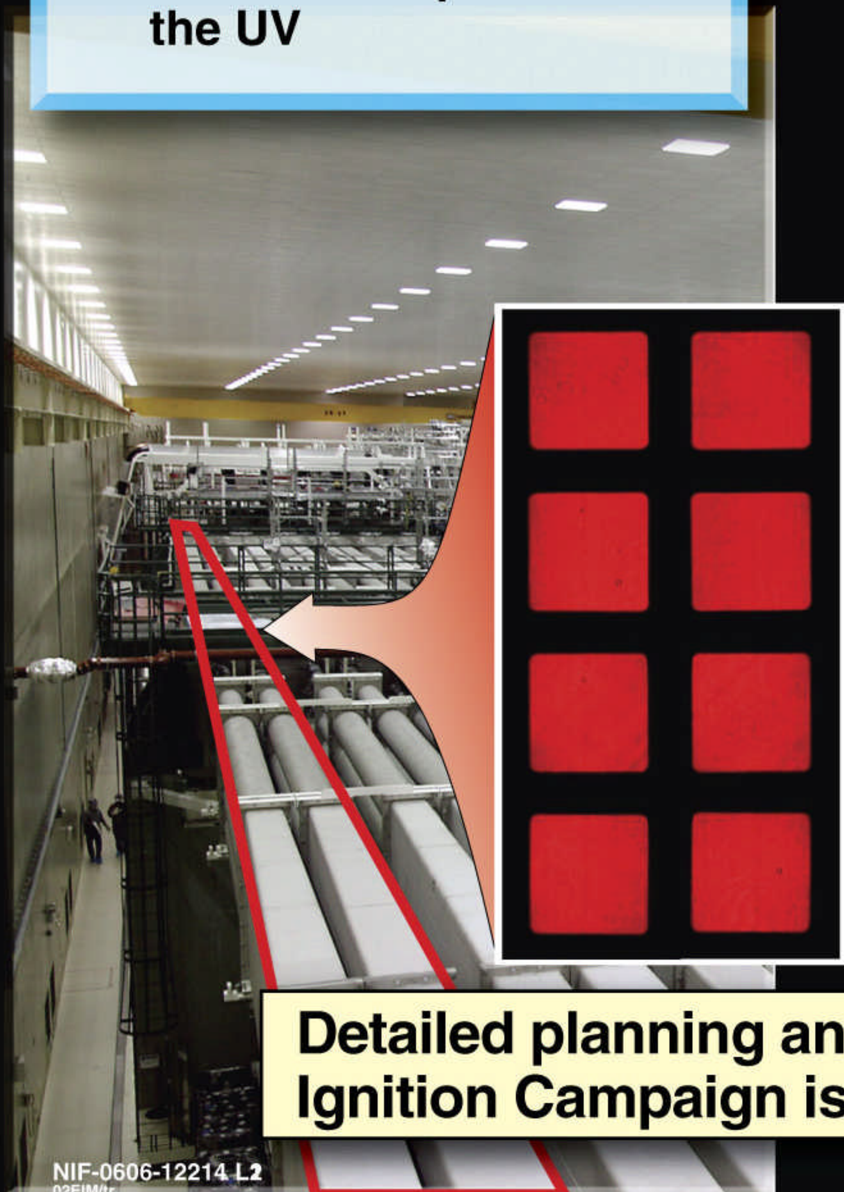
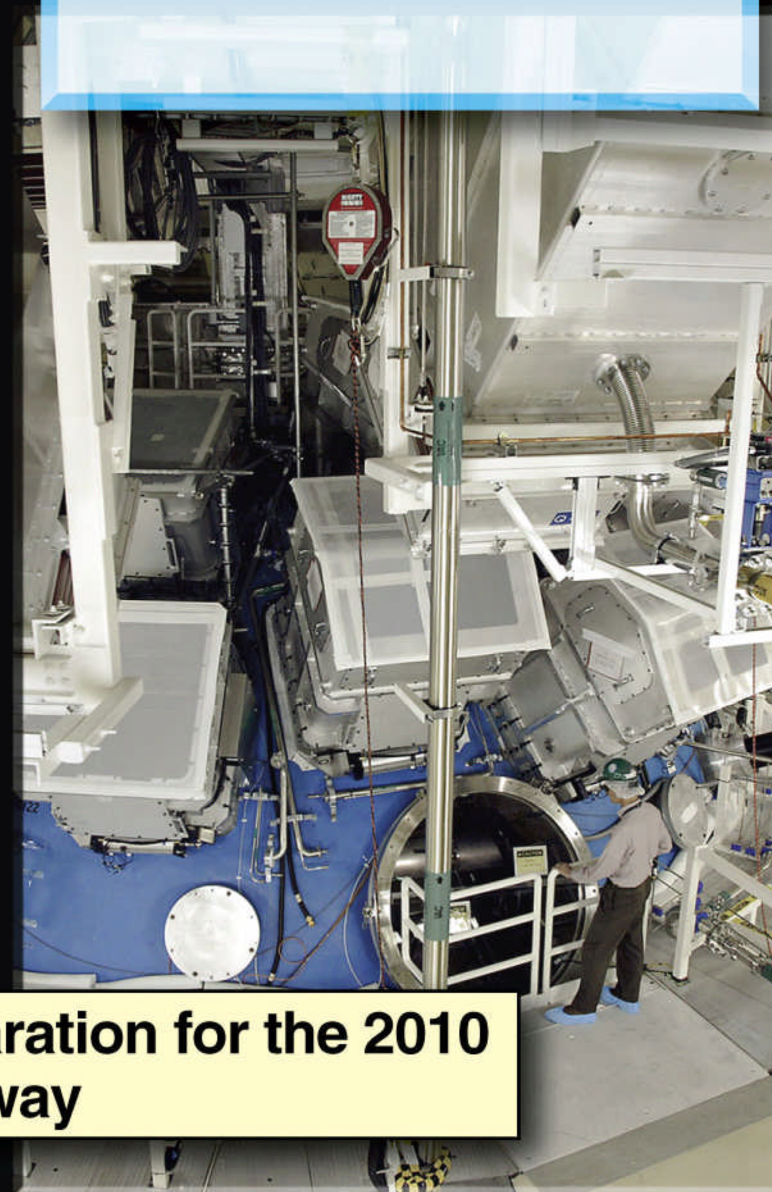
First experiments completed with one quad of beams

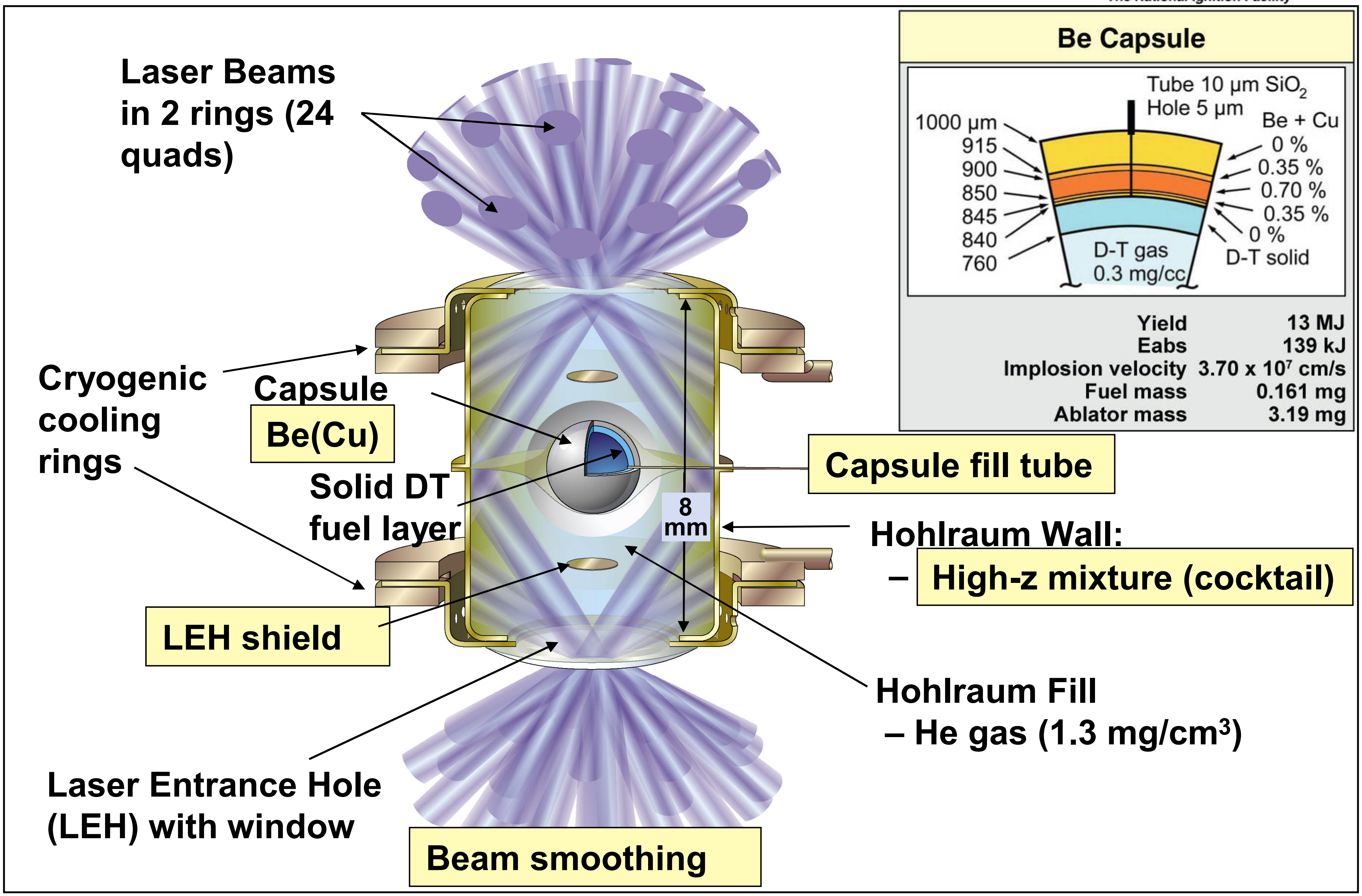




Detailed planning and preparation for the 2010 Ignition Campaign is underway

NIF-0606-12214 L2
02EIM/tr

The ignition point design includes important features to optimize performance



Maximizing energy coupling efficiency is an important component of the overall optimization

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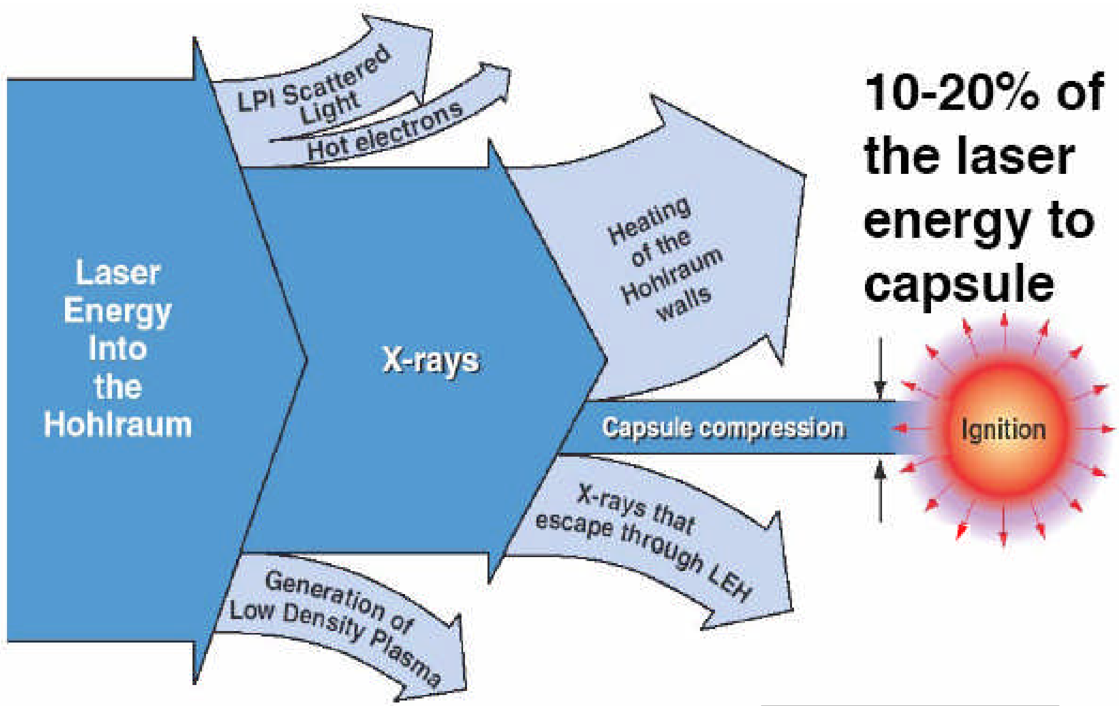

10-20% of the laser energy to capsule

	Au with CH capsule (1997)	Au with Be Capsule		Cocktails with Diamond capsule
Laser light (MJ)	1.45	1.08		1.0
Absorbed	1.30	0.97		0.9
Xrays	1.10	0.825		0.765
Wall loss	0.68	0.51		0.405
Hole loss	0.28	0.20		0.195
Capsule	0.14	0.14		0.165
Efficiency	9.7%	12.5%		16.5%

Assessment of target performance requires sophisticated simulations - including those in 3D

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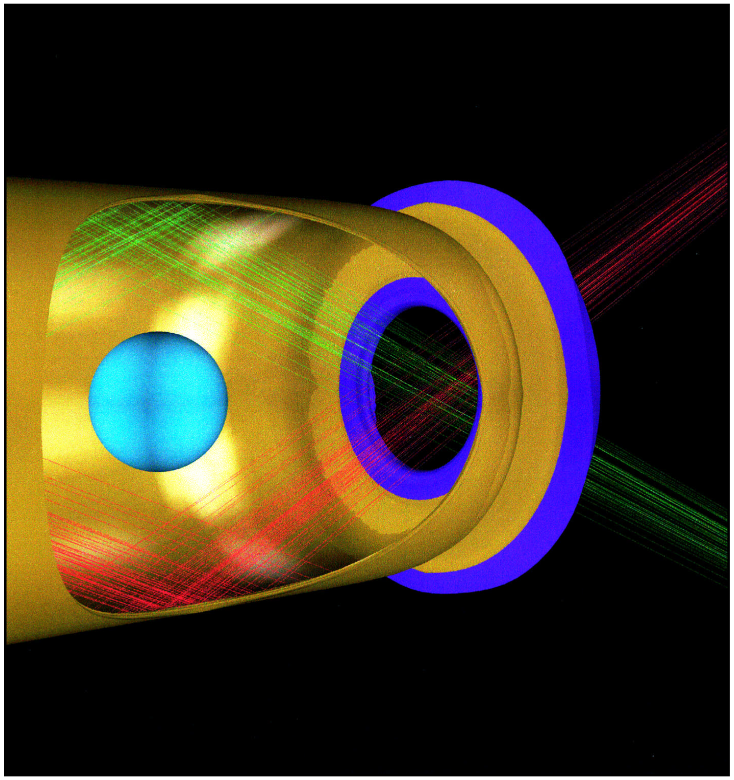
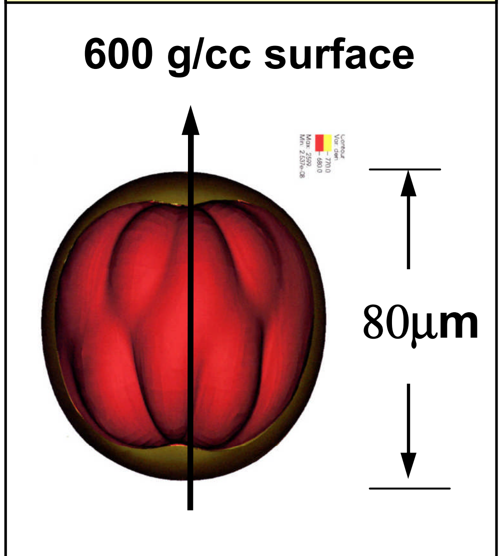
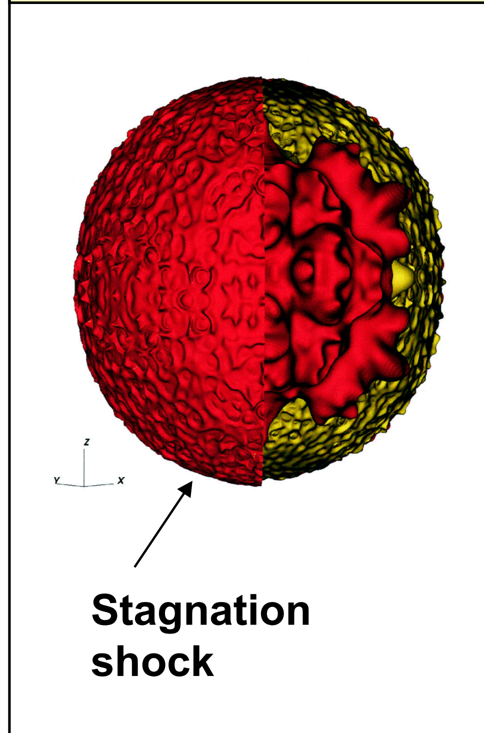


Ignition-hohlraum only perturbations



Hohlraum axis (z)

Ignition-capsule and hohlraum perturbations



400 g/cc density isosurface

Yields calculated in 3D are near 1D yields with both Gold and cocktail wall hohlraums and plastic or Be capsules

Be Capsule designs using graded dopants for pre-heat shielding have the best calculated performance

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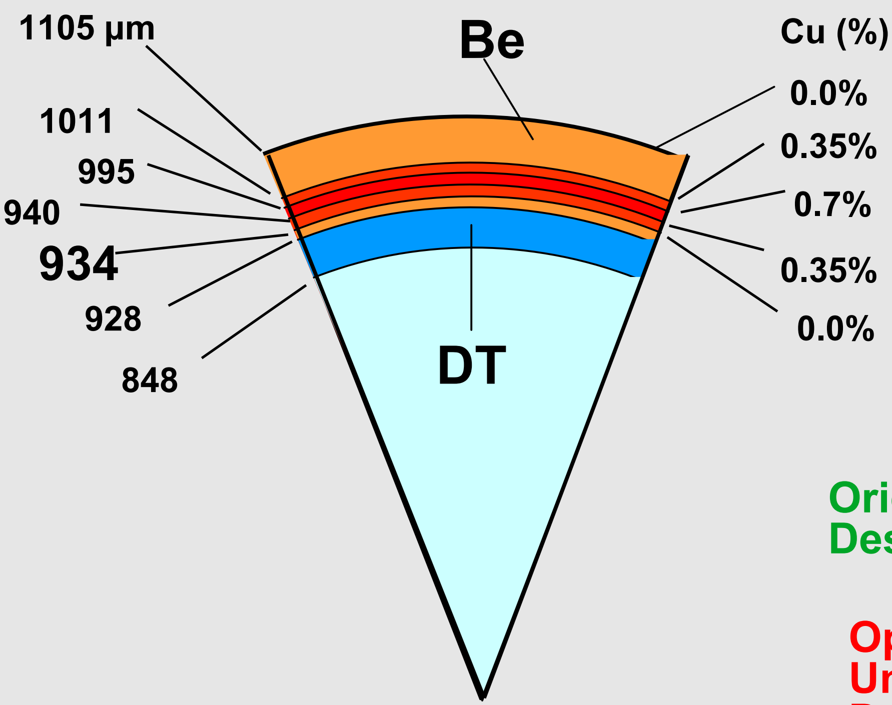
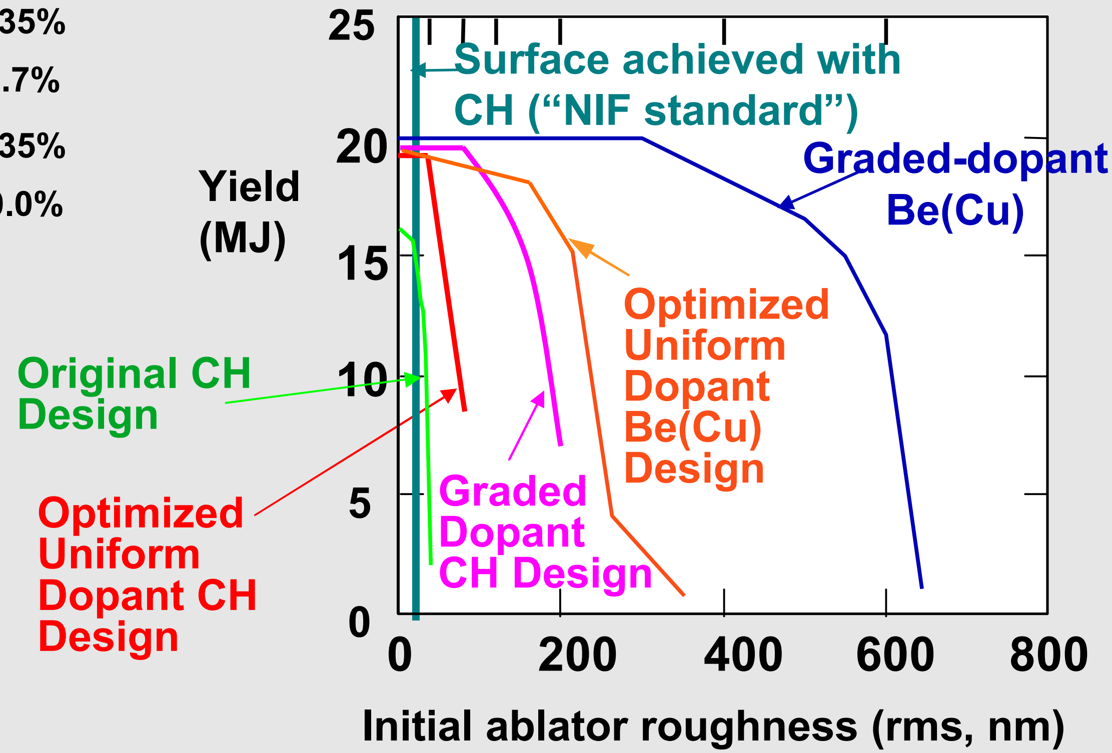
300 eV design:



1.8 MJ Design



Be is also about 2x more tolerant to ice roughness than CH capsules

Our first ignition experiments will be performed with 1 MJ of laser energy and the Graded-dopant Be Capsule

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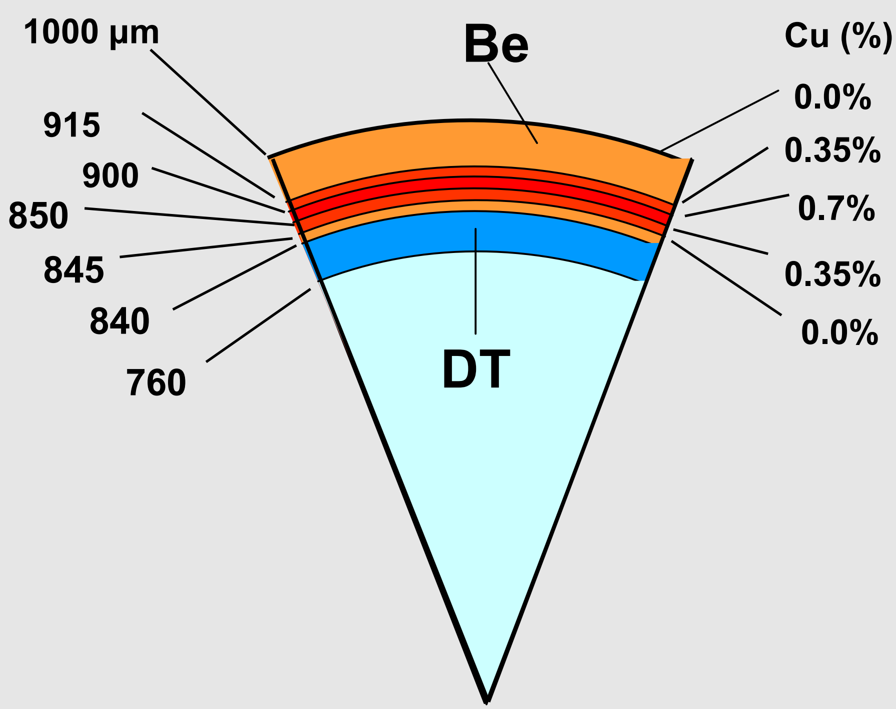
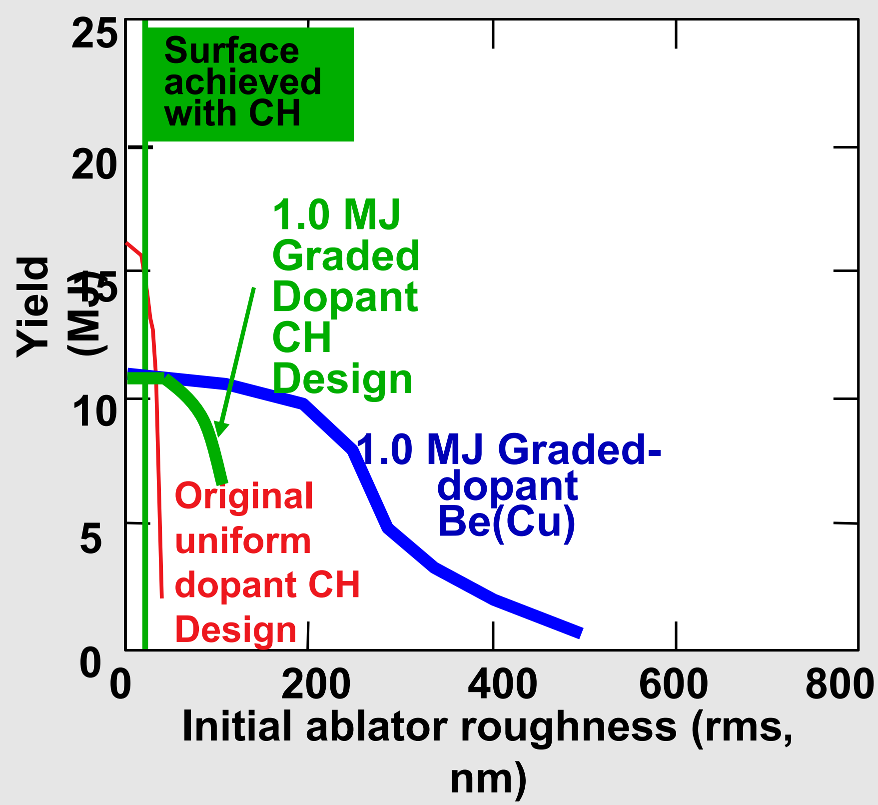
300 eV design:



1.0 MJ Design



Diamond is also an attractive ablator option

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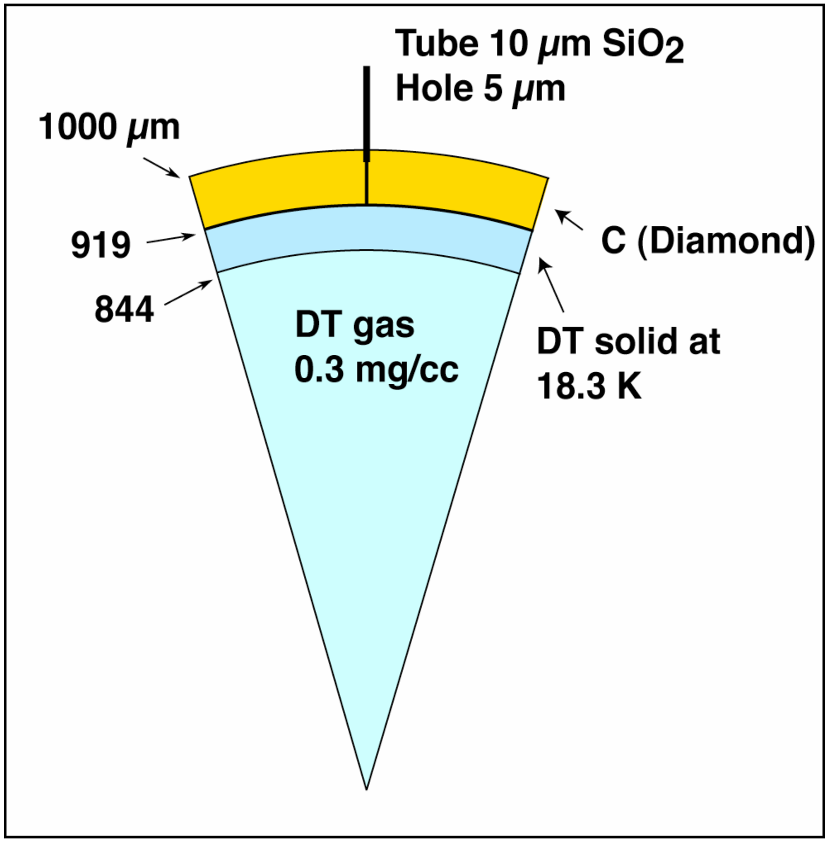

	Be	Diamond
Yield	13.6	17.0 MJ
Eabs	145	170 kJ
Implosion velocity	3.71	3.75 x 10^7 cm/s
Fuel mass	0.152	0.184 mg
Ablator mass	3.06	3.30 mg

- Higher density: diamond absorbs energy at larger radius → absorbs more energy. Equivalent to ~17% more laser energy.
- Surface roughness requirement similar g/cm^2, tighter in nm
- Tolerance of DT ice roughness very good, about 1.5-2x better than Be
- Encouraging progress in fabrication (CVD + polishing)

Simulations indicate that a 10 μm diameter tube has only a small impact on the implosion

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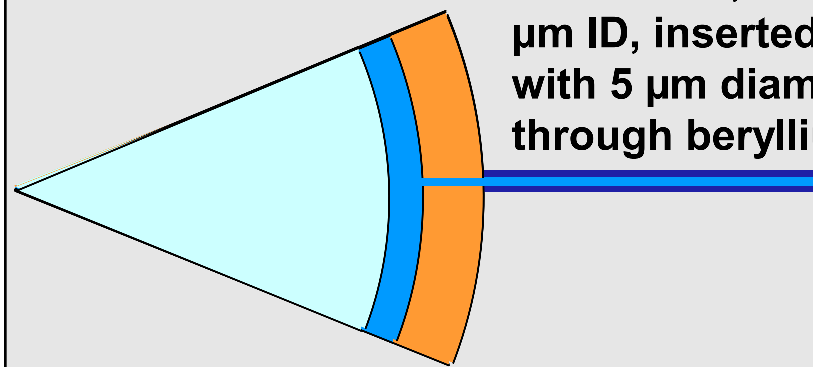
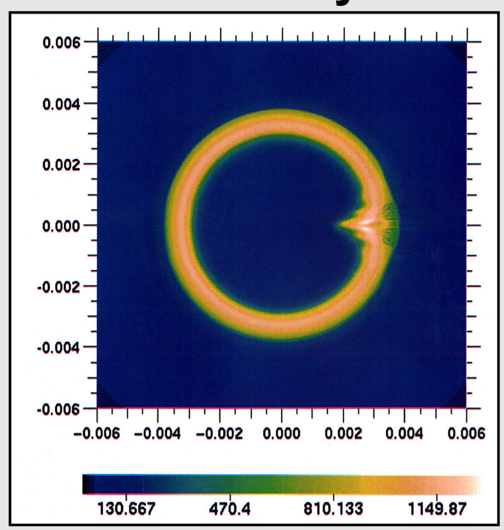
- Graded doped 140 kJ Be(Cu) capsule
- Calculation ignites and burns with near 1D yields (12.3 MJ)
- Contribution to the total hot spot perturbations is small
- We can make holes this size and are developing tube attachment techniques

~ 1.5-6 M cells to resolve hydrodynamics
~ 1 wk on 128 CPU

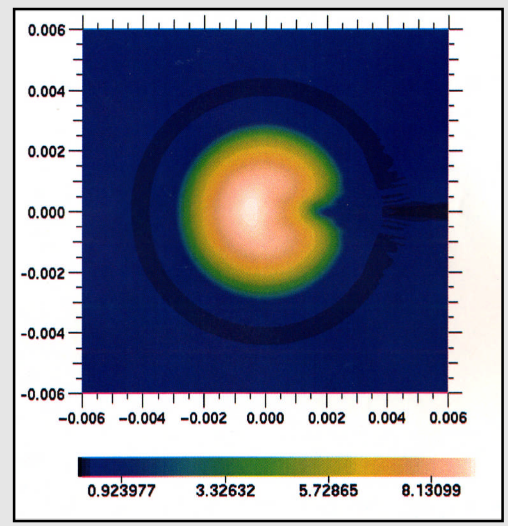


Glass tube, 10.8 μm OD, 5 μm ID, inserted 17 μm, with 5 μm diameter hole through beryllium ablator

Density

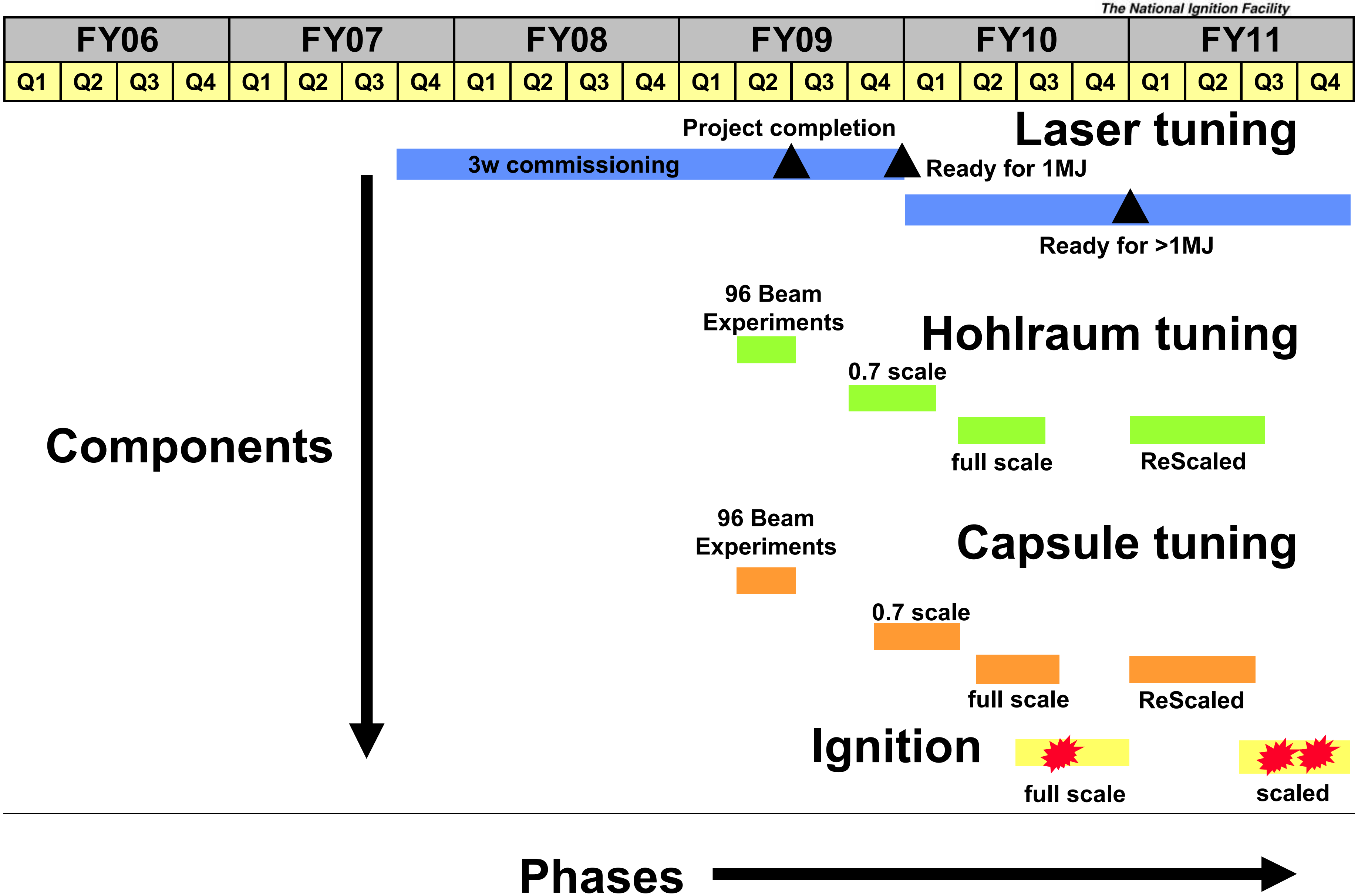


Temperature

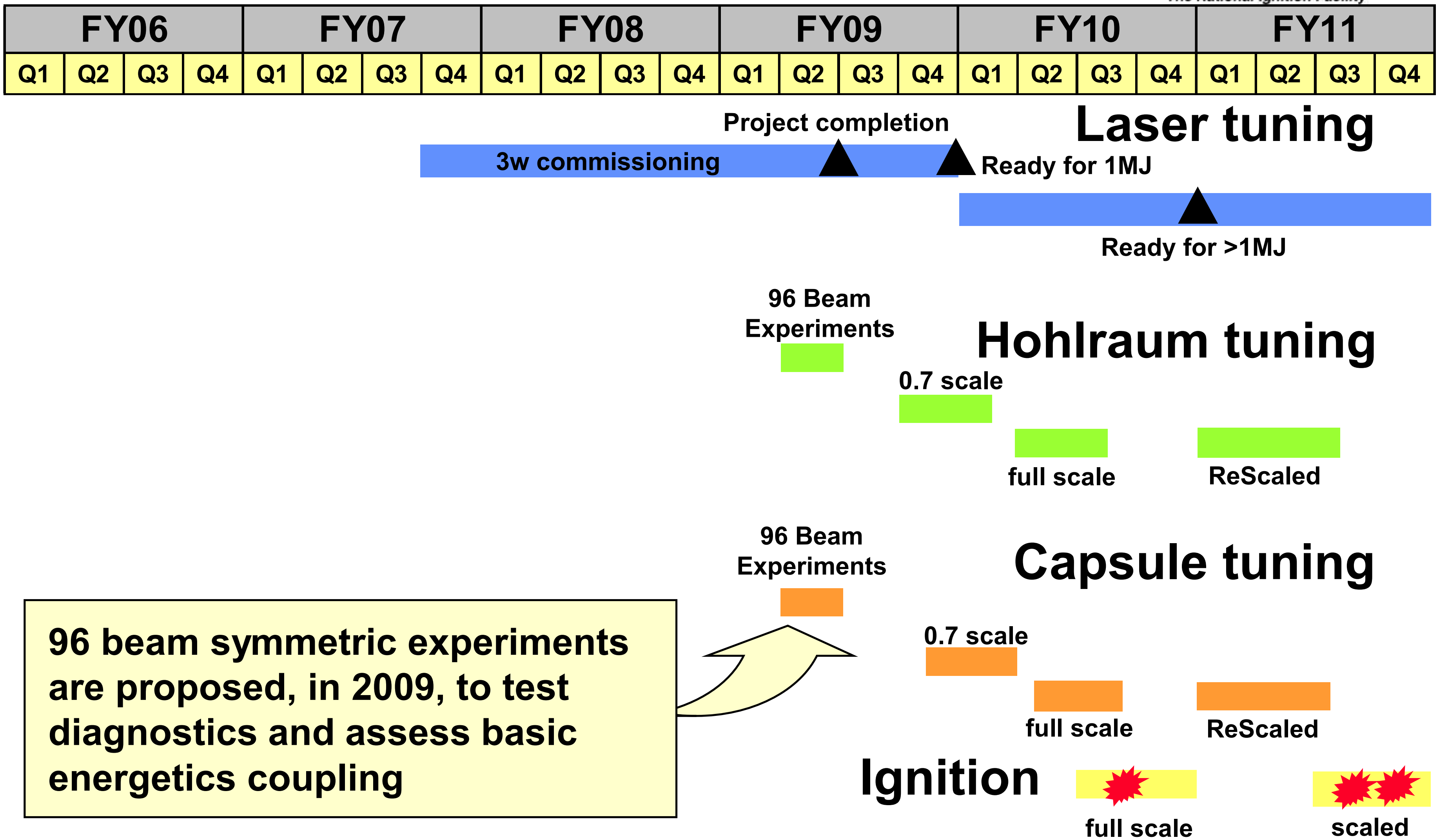


Ignition

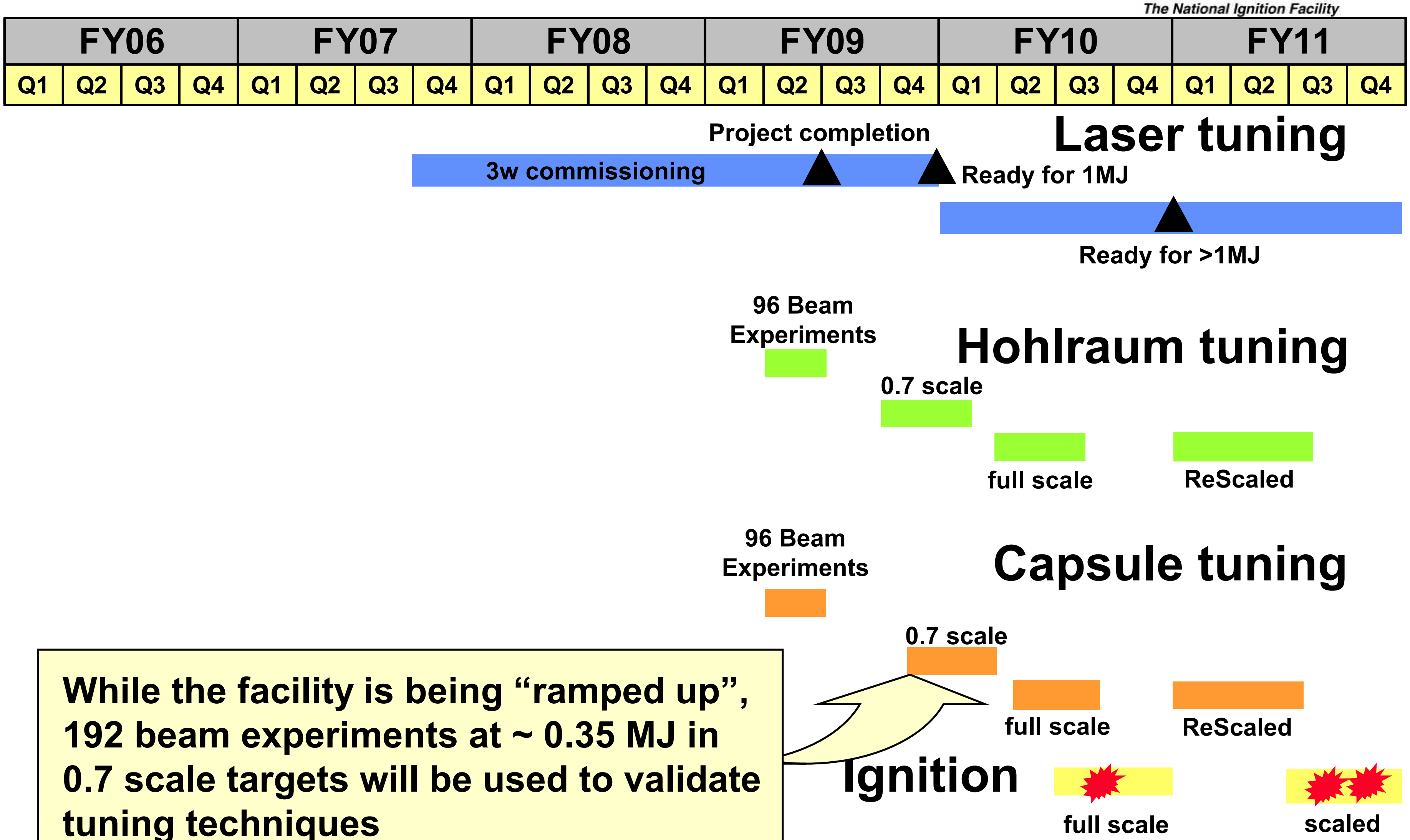
NIF campaigns will be phased in time and focus on different components of ignition



Early experiments in 2009 with 96 beams

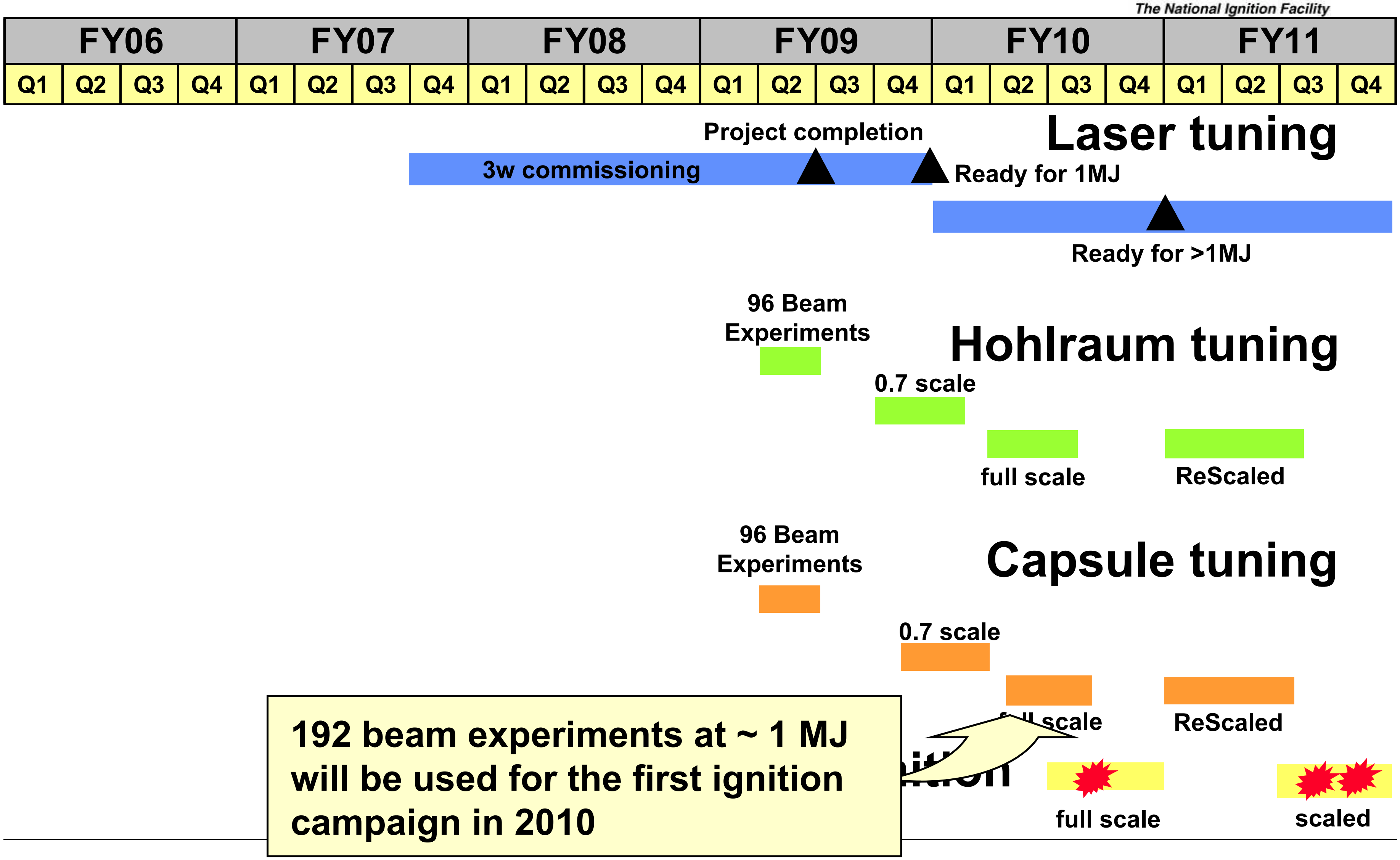


0.35 MJ - "scale 0.7" experiments with 192 beams



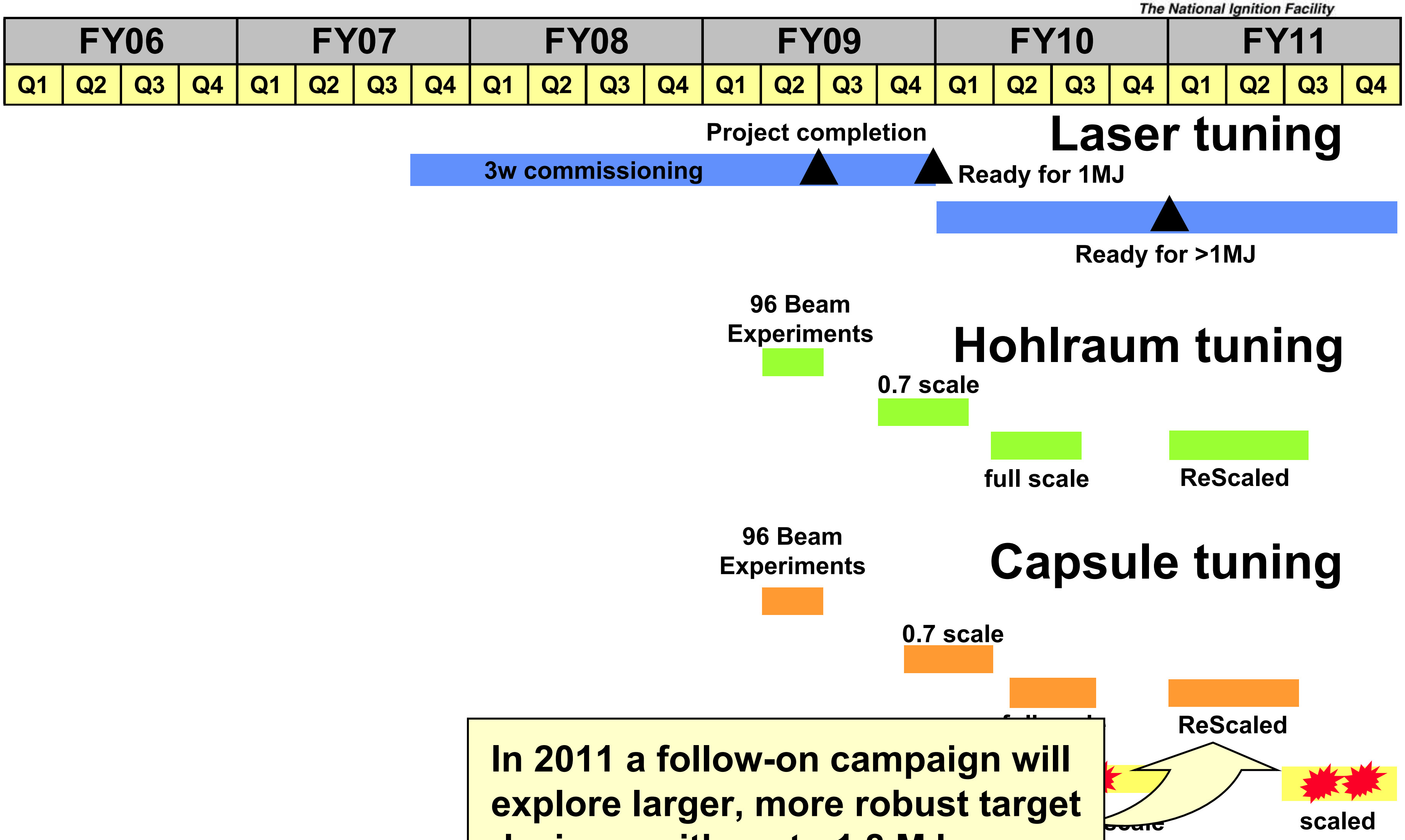
While the facility is being "ramped up", 192 beam experiments at ~ 0.35 MJ in 0.7 scale targets will be used to validate tuning techniques

1 MJ – “scale-1” ignition campaign in 2010



192 beam experiments at ~ 1 MJ will be used for the first ignition campaign in 2010

Follow-on campaign in 2011



In 2011 a follow-on campaign will explore larger, more robust target designs, with up to 1.8 MJ

NIF Experimental plan for ignition consists of campaigns with specific goals

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- Hohlraum Tuning
  - *Energetics*
    - Reach desired radiation temperature
  - *Symmetry*
    - Ensure spherically symmetric x-ray illumination of capsule throughout implosion
- Capsule Tuning
  - *Ablator Performance*
    - Ensure morphology leads to acceptable hydrodynamic stability
    - Ensure correct peak velocity implosion without burning through ablator
  - *Shock Timing*
    - Ensure specified shock coalescence for isentropic fuel compression
- Ignition
  - Measure target yield and other nuclear signatures

The Energetics Campaign will confirm required radiation temperature in ignition hohlraums

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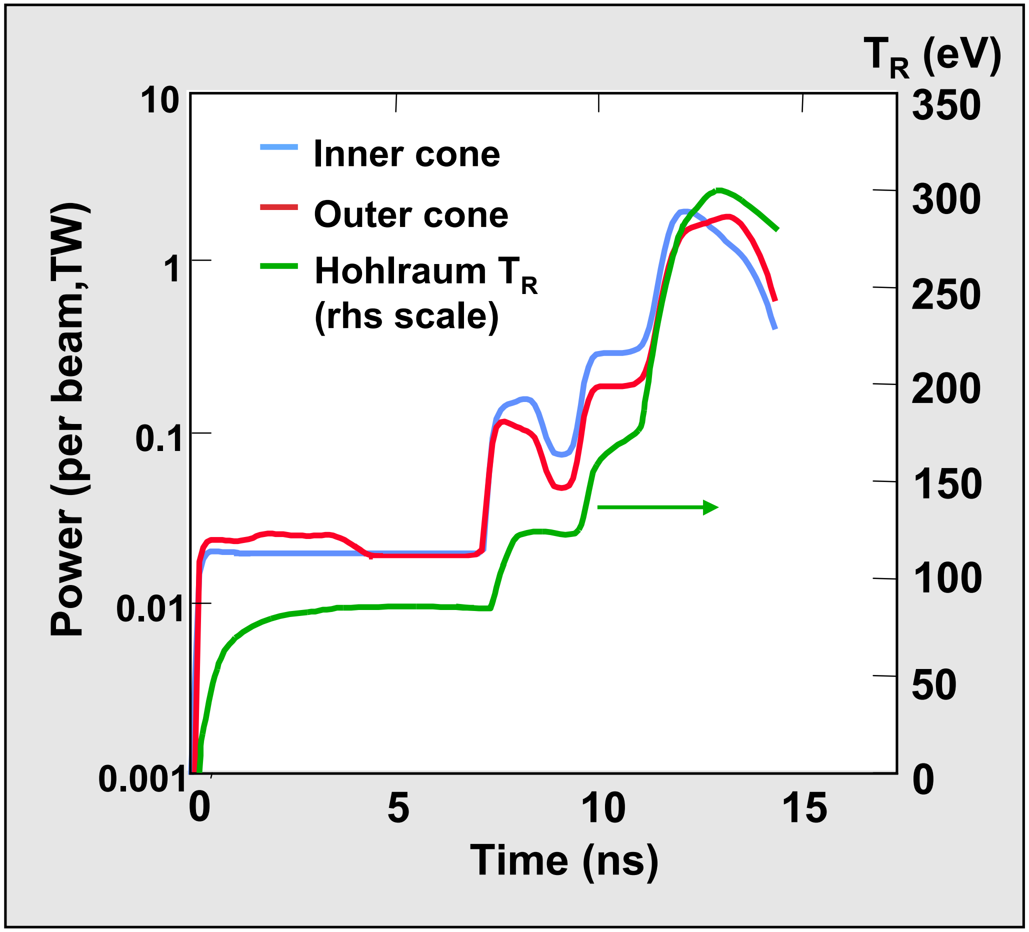
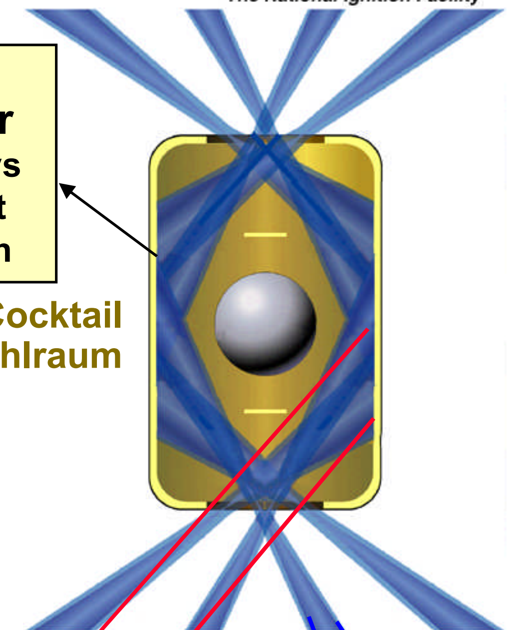


Hard X-ray Spectrometer
10-100 keV x-rays for inferring hot electron fraction



Hohlraum T_R
18 channel soft x-ray detector (0.1- 10 keV)

Backscatter and Near Backscatter Diagnostics
Time and spectrally resolved scattered power

Requirements: Peak T_R of 300 eV
Match desired shape to <10% in x-ray flux
Hot electron fraction < 1% for T_H = 30 keV

NEL experiments activated the hohlraum drive diagnostics up to ignition relevant T_R

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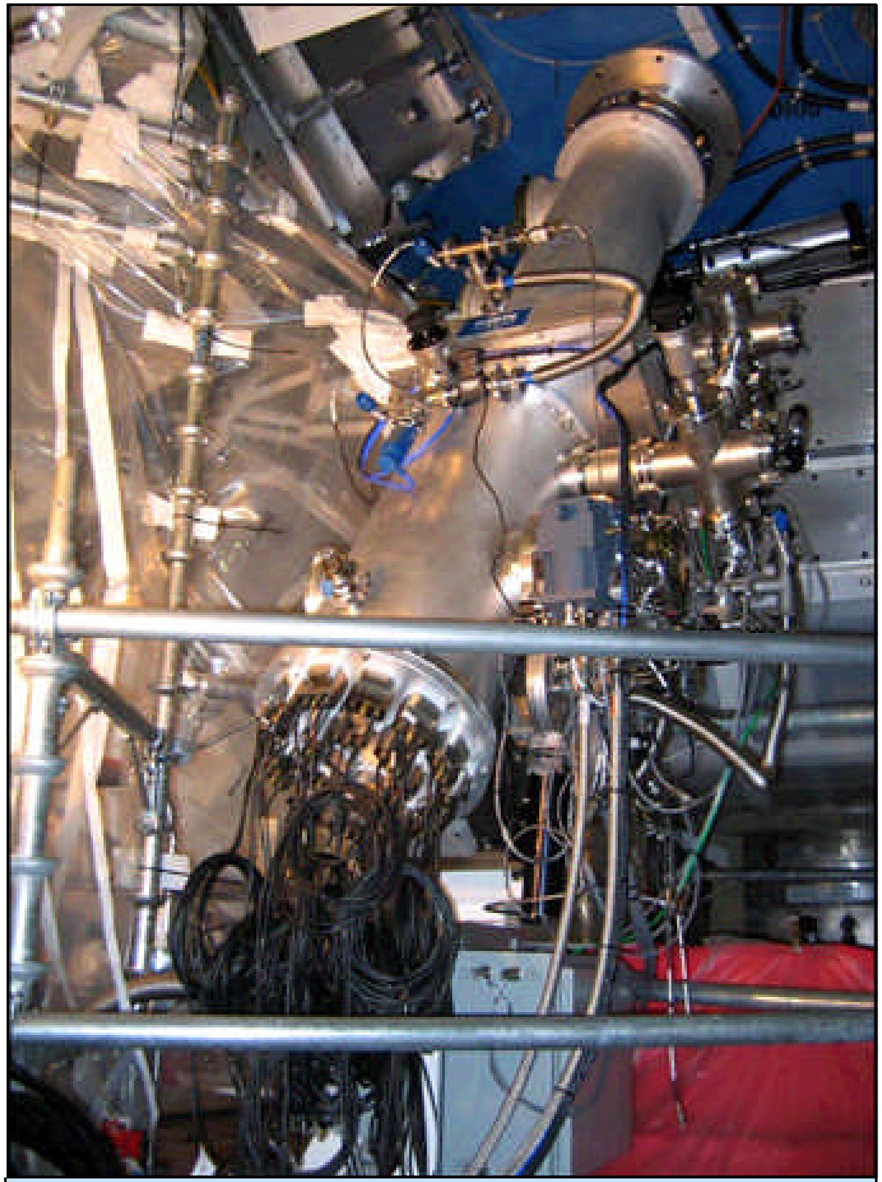
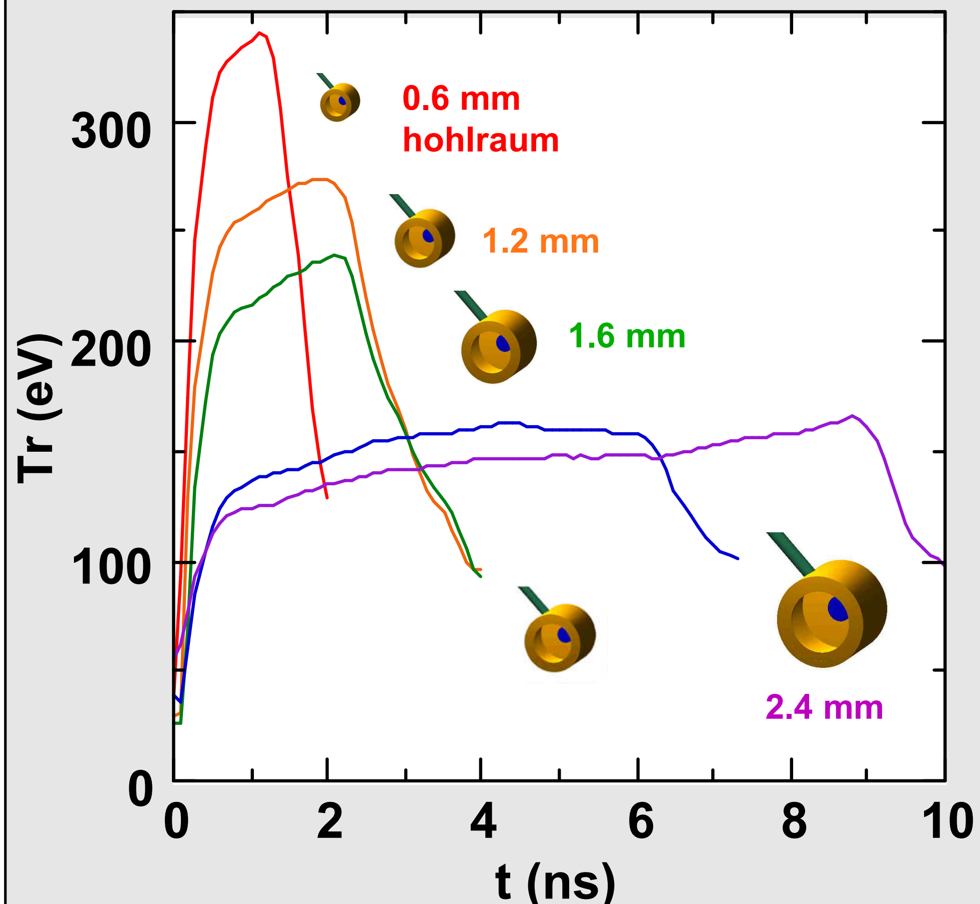


Dante diode array – time resolved radiation drive

Hohlraum T_R vs time



4-16 kJ, 1- 9 ns, 10^{15}-10^{16} W/cm^2

An international team has successfully activated hohlraum diagnostics at NIF and the first hohlraum experiments are in close agreement with calculations

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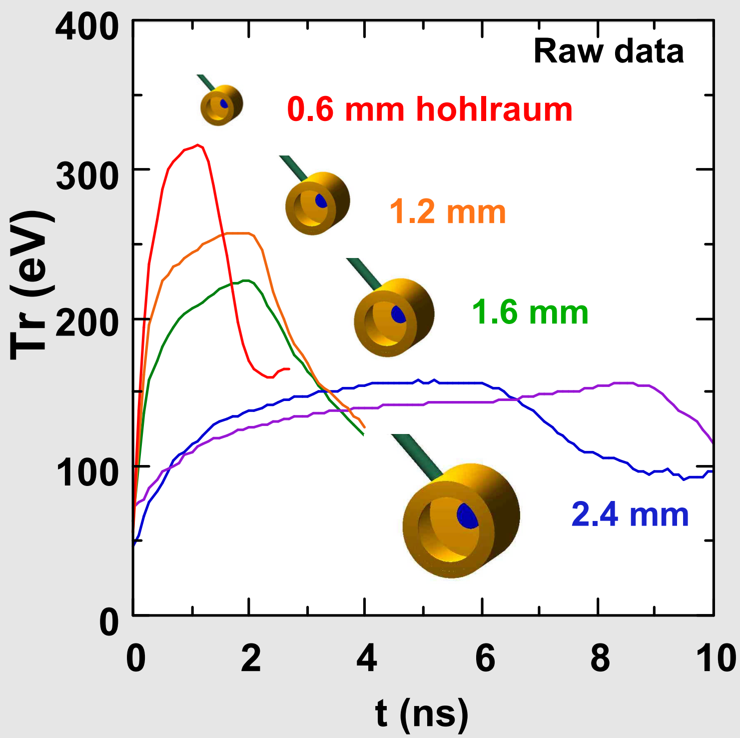
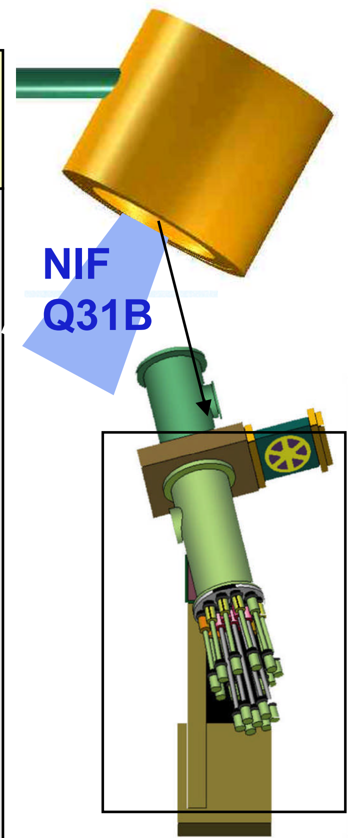
Hohlraum Tr vs time

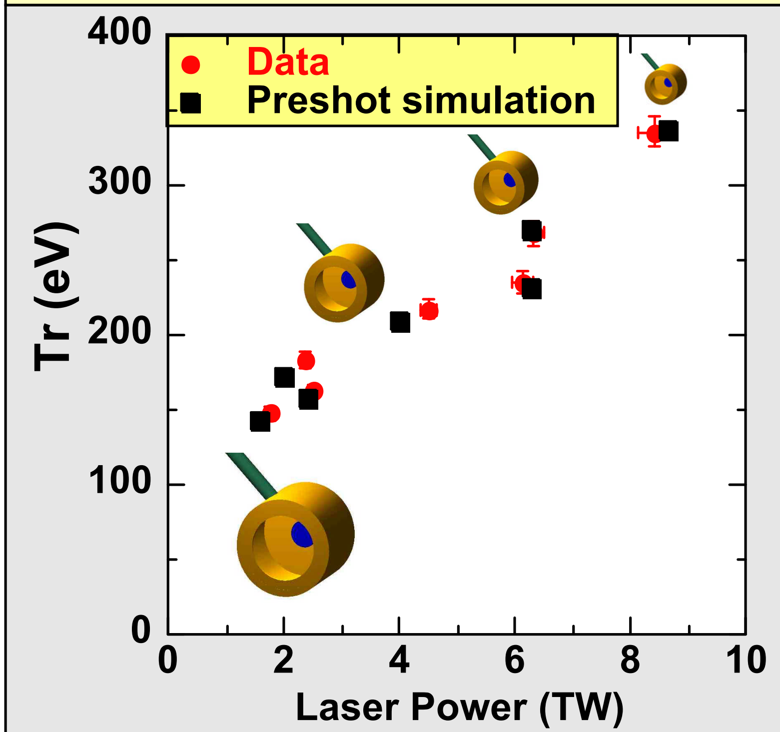


Thinwall Au Hohlraum

4-16 kJ, 1- 9 ns, 10^{15}-10^{16} W/cm^2 with beam smoothing



Peak Hohlraum Tr vs Laser Power



Hohlraum Tr (Dante)

18 channel soft x-ray detector (0.1- 10 keV)

Los Alamos NATIONAL LABORATORY

Sandia National Laboratories

AWE

cea

Recent cocktail hohlraums demonstrate expected soft x-ray flux increase over gold hohlraums

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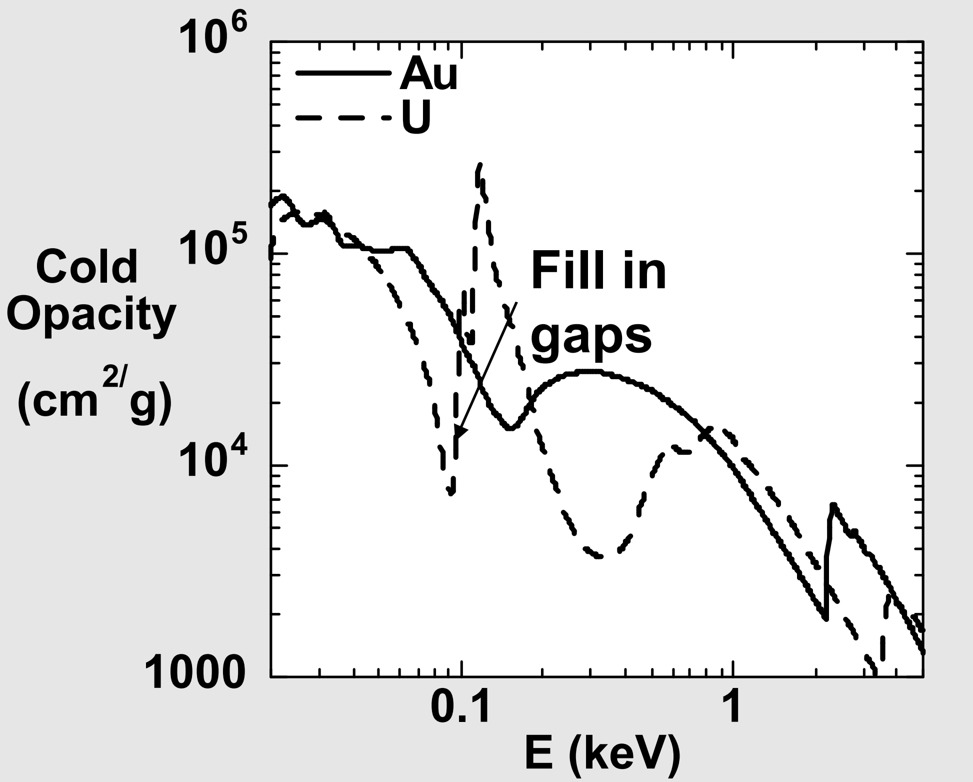
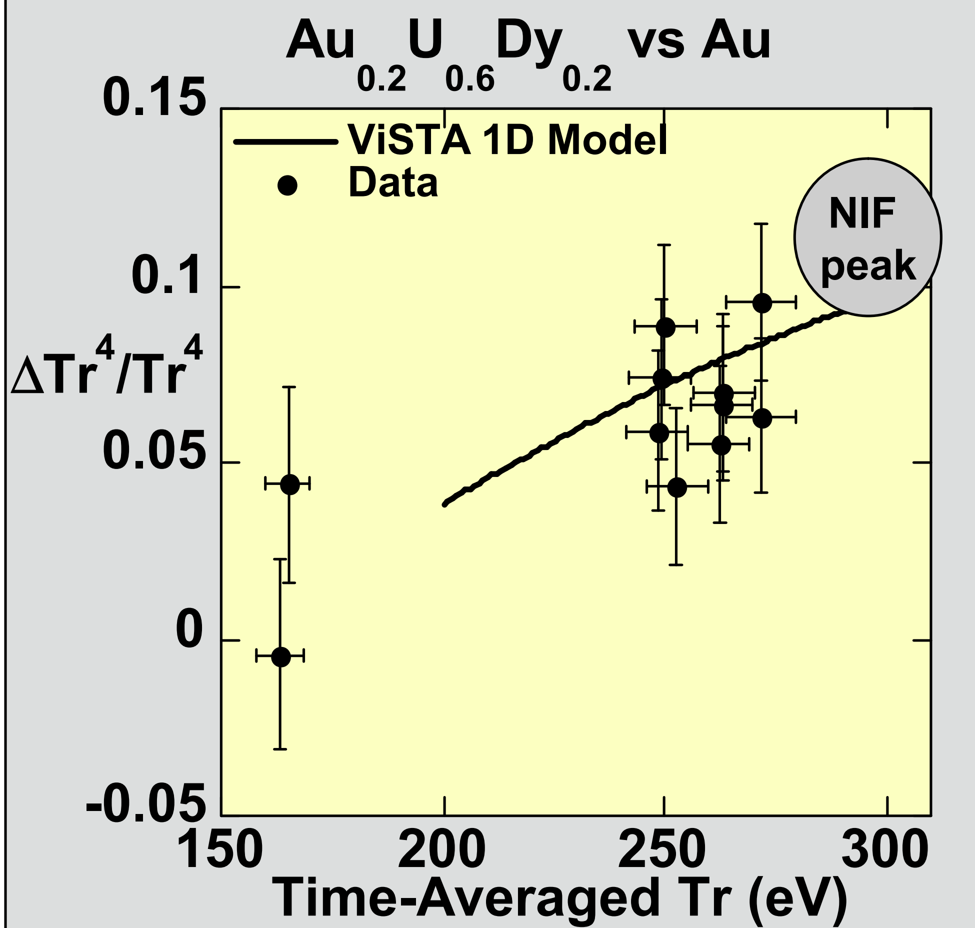
Use mixture of materials to increase Rosseland mean opacity





Filamentation or scattering can change the incident energy or the spatial distribution of the incident laser beam

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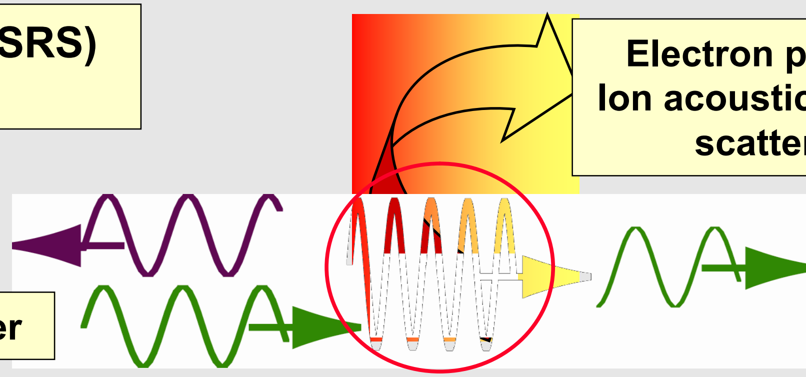
Stimulated Raman scattering (SRS) and Brillioun (SBS) scattering

Electron plasma wave and Ion acoustic wave in plasmas scatter laser beam

Incident Laser

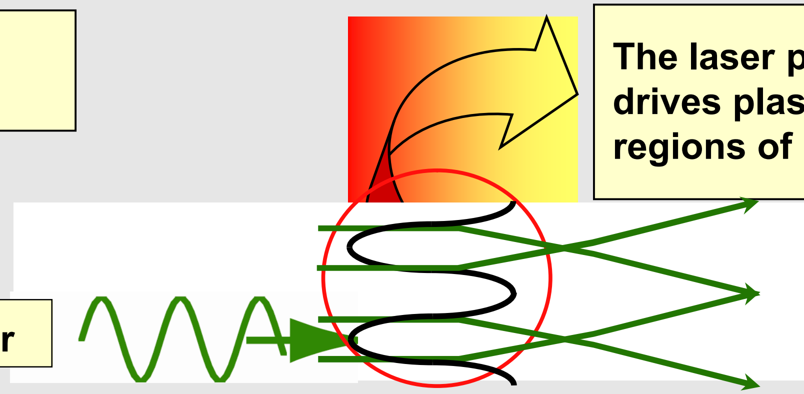


Transmitted Laser

Filamentation or whole beam self-focusing

The laser ponderomotive force drives plasma away from regions of high intensity

Incident Laser

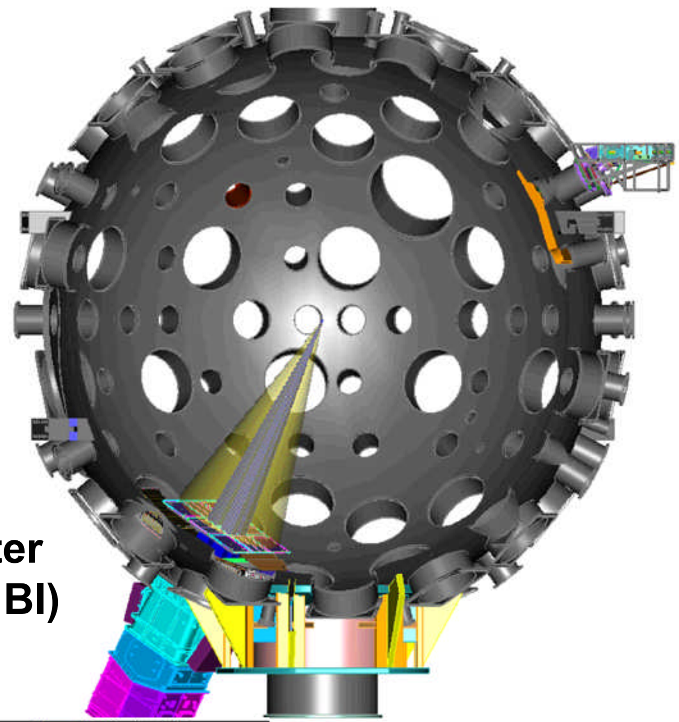


Density contour

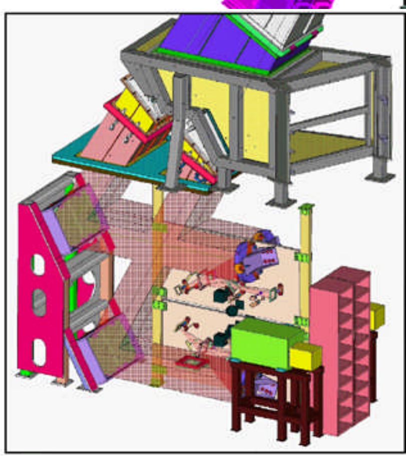
Light refracts towards the density minimum –increasing the light intensity

We can mitigate backscatter by beam smoothing, reducing laser intensity and/or varying plasma composition

Backscatter diagnostics were activated on NEL experiments

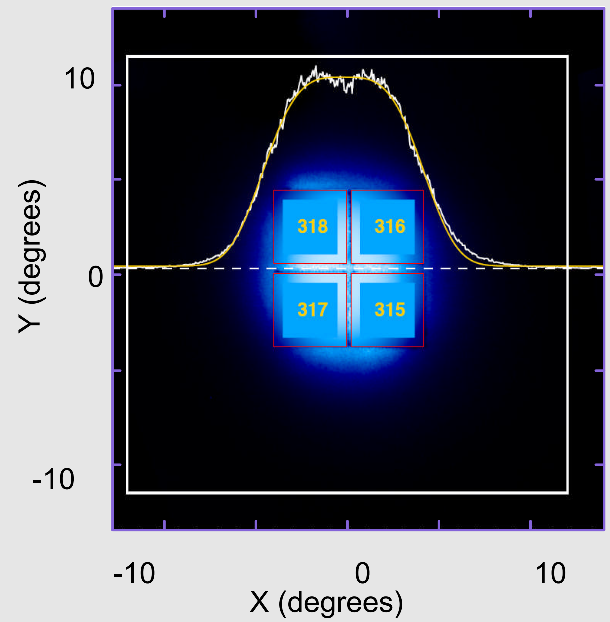


Near backscatter imager (NBI)

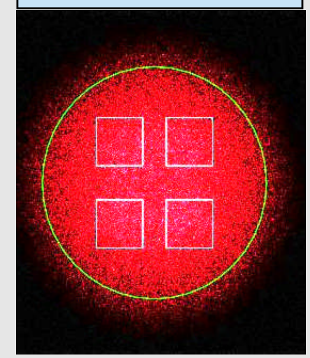


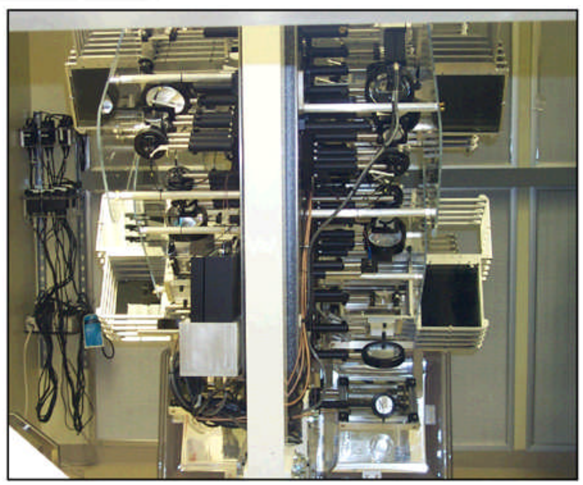
Full aperture backscatter (FABS)

Measure backscatter into and around lenses



pF3D model





- **FABS: Temporally and spectrally resolved SBS and SRS backscatter**
- **NBI: SBS and SRS backscatter around lenses**

"Beam Smoothing" has several elements

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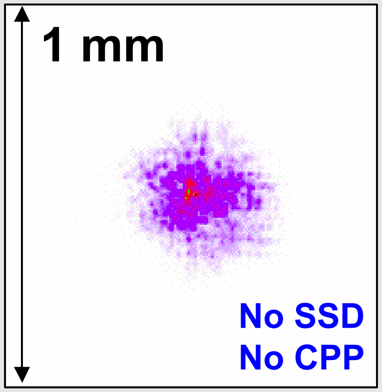
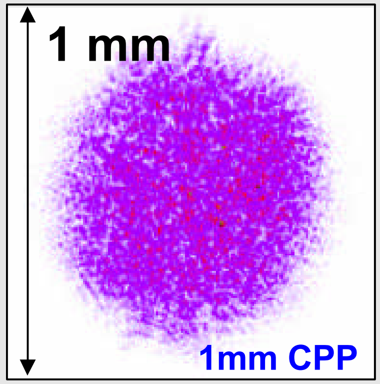
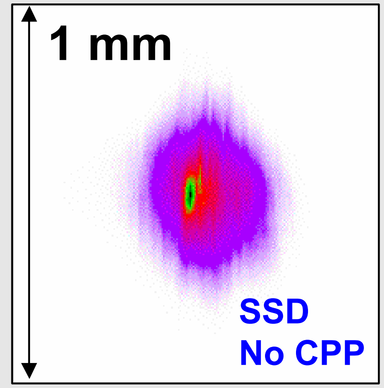
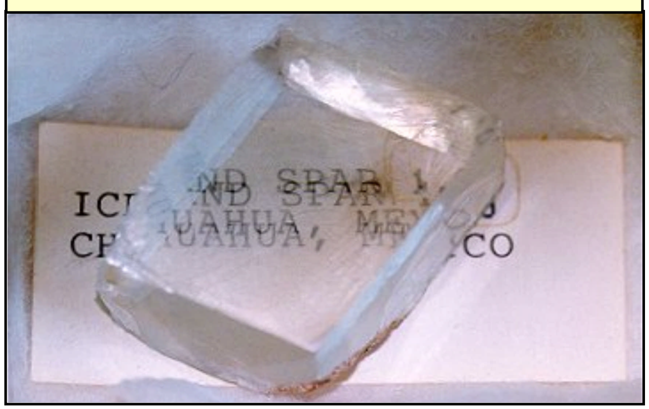
No CPP	With CPP	With SSD
Stationary speckles		Time-averaged pattern
		
CPPs determine the spot size and the control intensity distribution		SSD moves hot spots on short time scales (~4 ps)

Polarization smoothing



Polarization smoothing doubles the speckles giving instantaneous $\sqrt{2}$ intensity reduction

The Symmetry Campaign sets the beam pointing and cone power ratio to optimize x-ray drive symmetry

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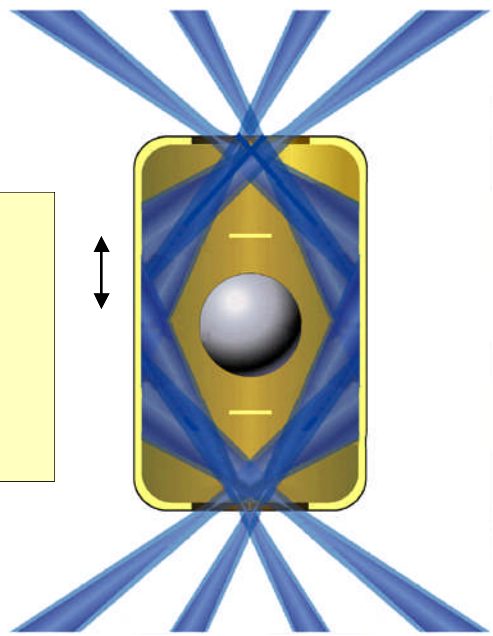
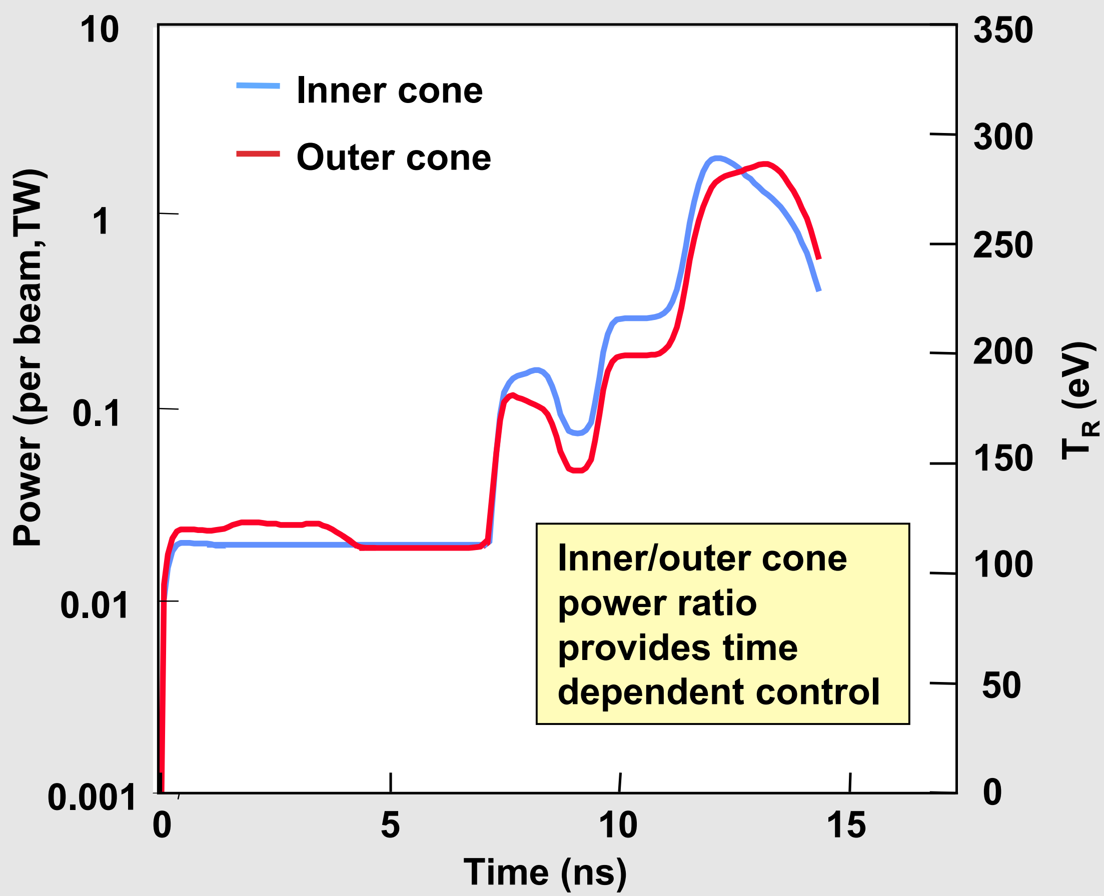
Time Integrated Symmetry
Inner-Outer beam pointing

Pointing provides time-integrated symmetry control



Requirements:
rms asymmetry to < 1% flux

Time Dependent Symmetry
Inner/Outer cone power ratio



Requirements: < 20/Δt % for asymmetry swings over time interval Δt (ns)

The Symmetry Campaign sets the beam pointing and cone power ratio to optimize x-ray drive symmetry

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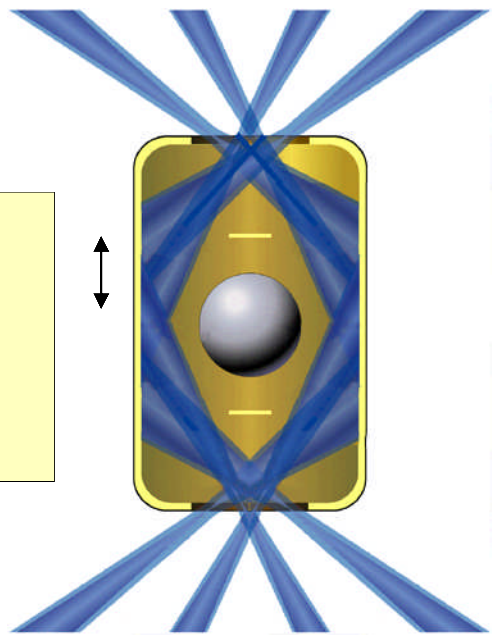
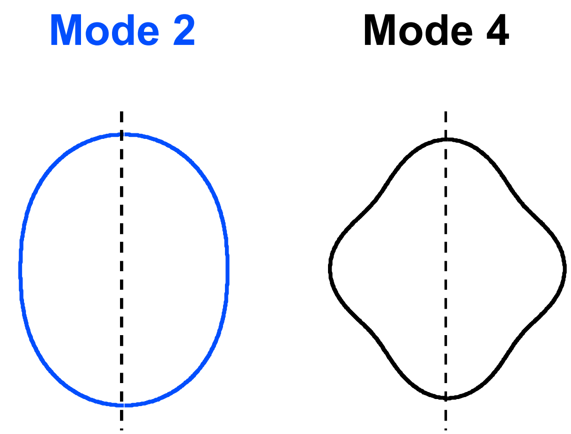
Time Integrated Symmetry Inner-Outer beam pointing

Pointing provides time-integrated symmetry control



Requirements:
rms asymmetry to < 1% flux

Examples of lowest order Legendre modes (P_n/P_0 = 20%)



QuickTime™ and a
Uncompressed) decompressor
needed to see this picture.

QuickTime™ and a
Uncompressed) decompressor
needed to see this picture.

Requirements: < 20/Δt % for asymmetry swings over time interval Δt (ns)

A suite of symmetry measurement techniques has been developed

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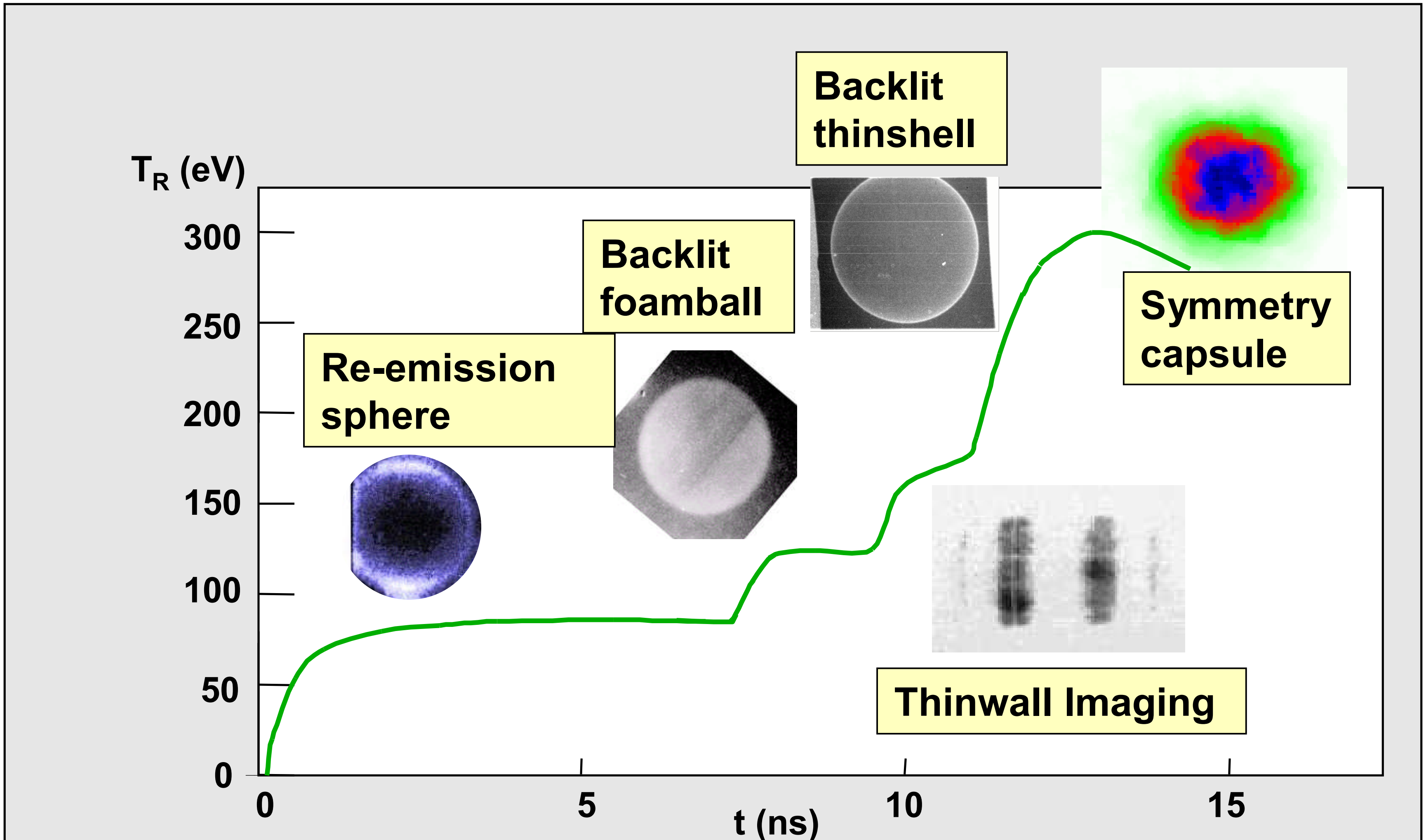

Techniques have been deployed in vacuum, gas-filled and foam-filled hohlraums, at up to NIF-scale

J. Lindl, Phys. Plasmas (2004)

We will use these techniques to build up required symmetry through the pulse

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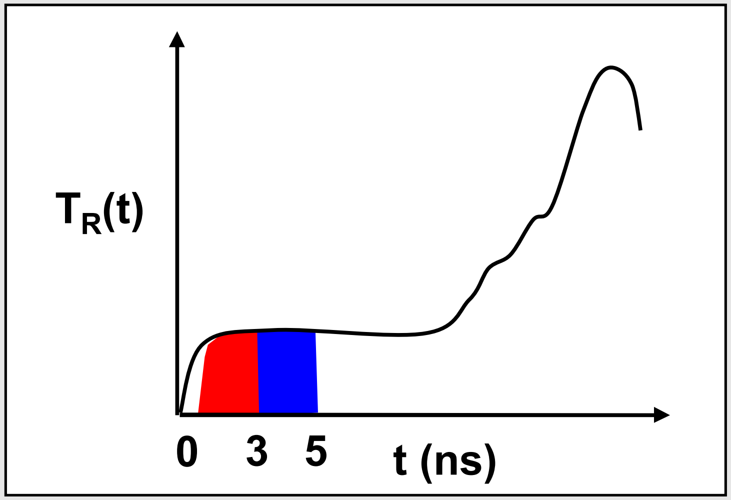
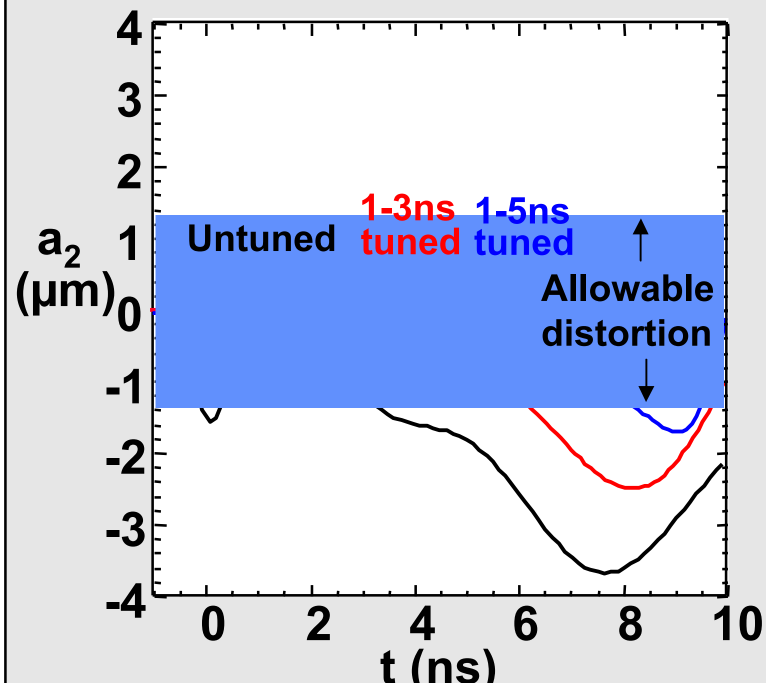
Schematic showing tuning in successive 2 ns window intervals



Truncated in time laser pulses will be used to provide more conducive laser and measurement environment

Example: Calculated 0.1 g/cc SiO_2 foamball a_2 asymmetry

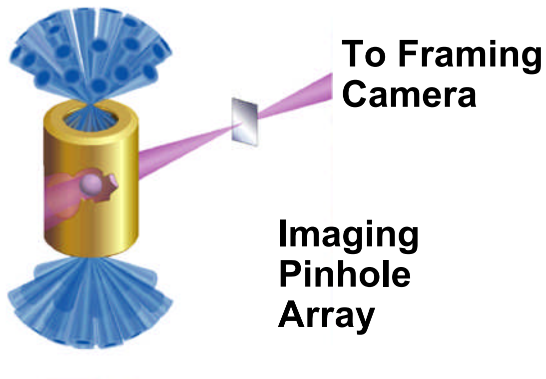


Distortions reduced to below requirement threshold

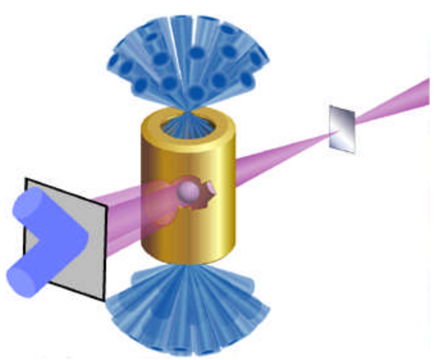
The Symmetry Campaign uses capsule surrogates to infer x-ray drive symmetry

Multiple capsule surrogates

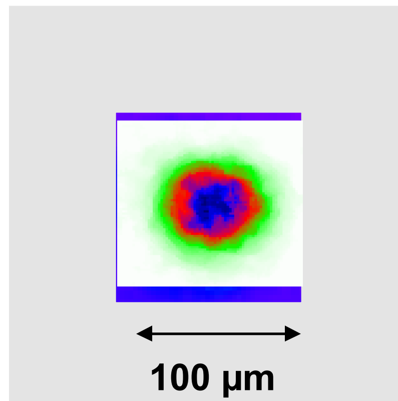
Capsule or Re-emit in Self-emission

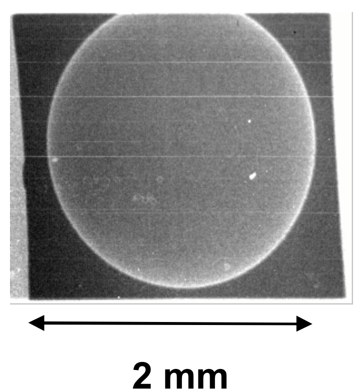


Backlit foamball or thinshell



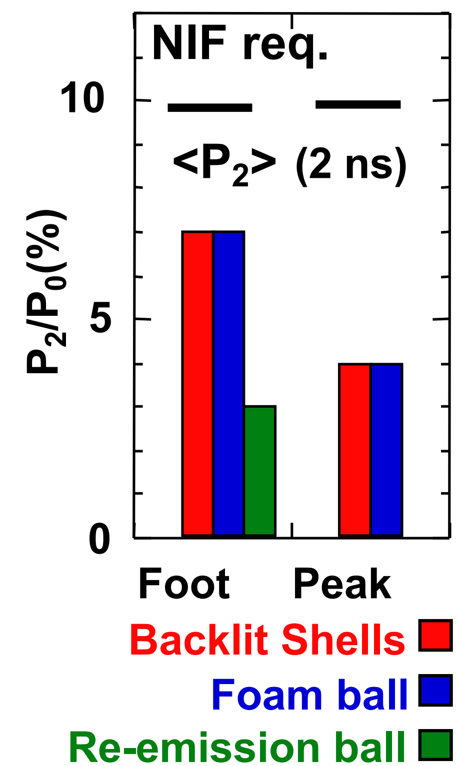
X-ray images used to infer asymmetry





Existing data extrapolates to required accuracy

Example



The Ablator Performance Campaign will confirm acceptable morphology, and fine tune the ablator thickness and dopant concentration

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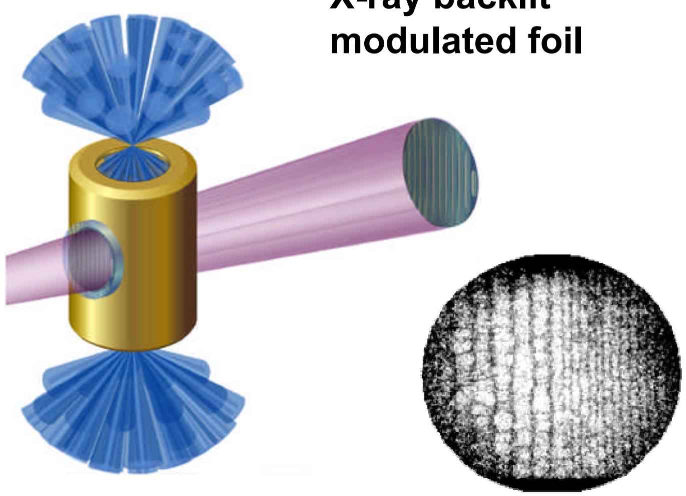
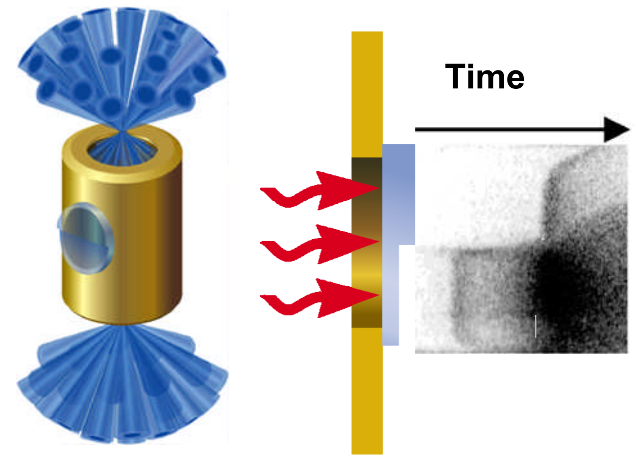
Measure instability growth from initial morphology



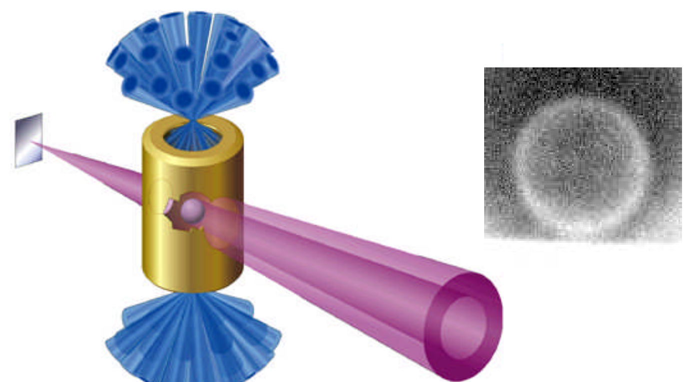
Check Be morphology

Measure burn-thru to optimize ablator thickness

Planar



Convergent



Specify ablator thickness to 1%

Multiple techniques are being evaluated for convergent ablation rate:

e.g. X-ray Radiography, Areal density inference from charged particle stopping or Cu activation, bangtime

A Rayleigh-Taylor experiment with growth factors > 1000 will be used to validate Be ablators on NIF

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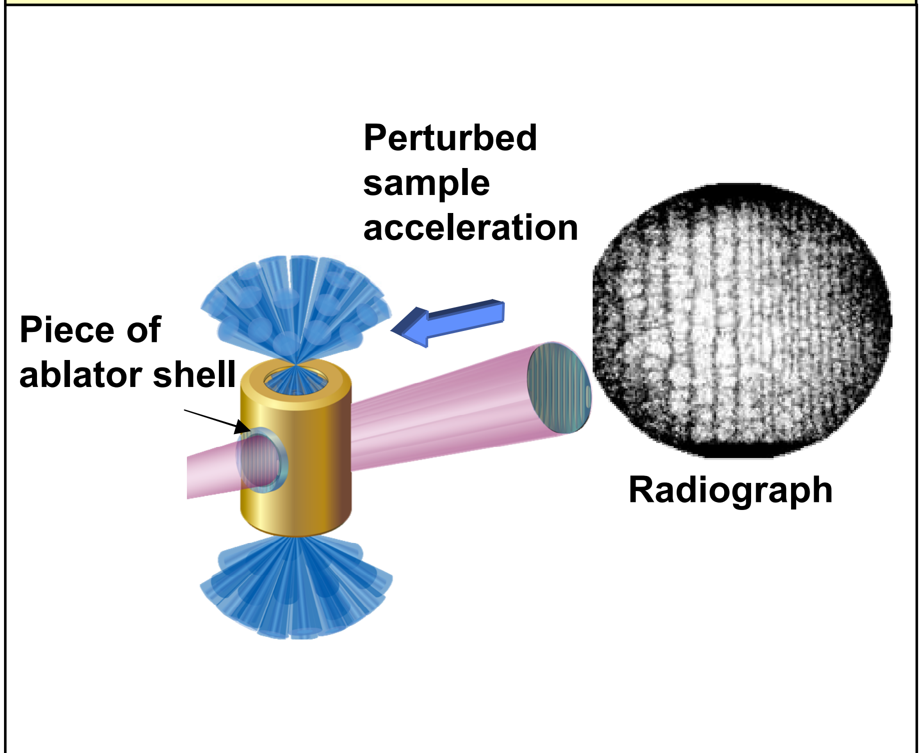
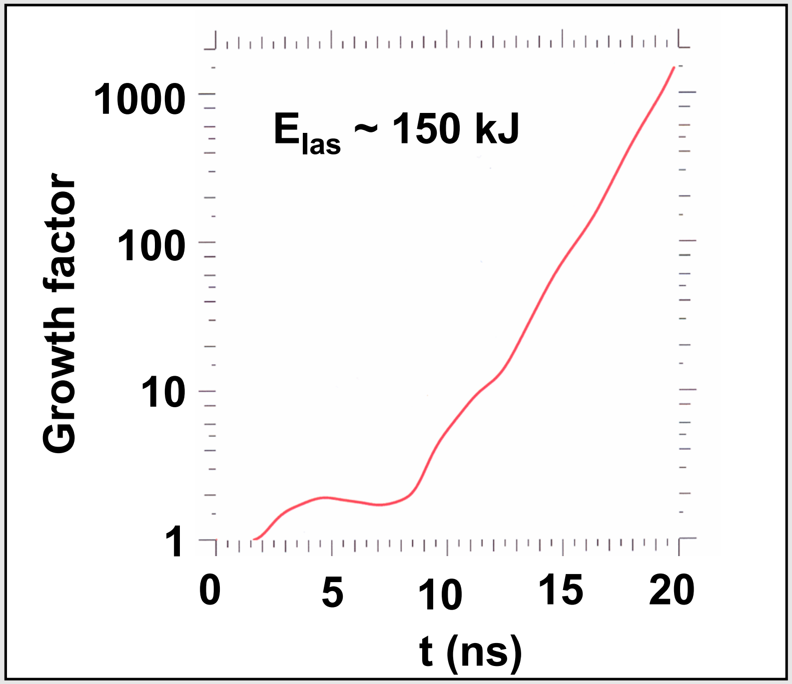
Schematic of NIF experiment



Single mode growth factor vs time



The Shock Timing Campaign will fine tune the timing of the steps in the laser pulse to reach desired shock coalescence

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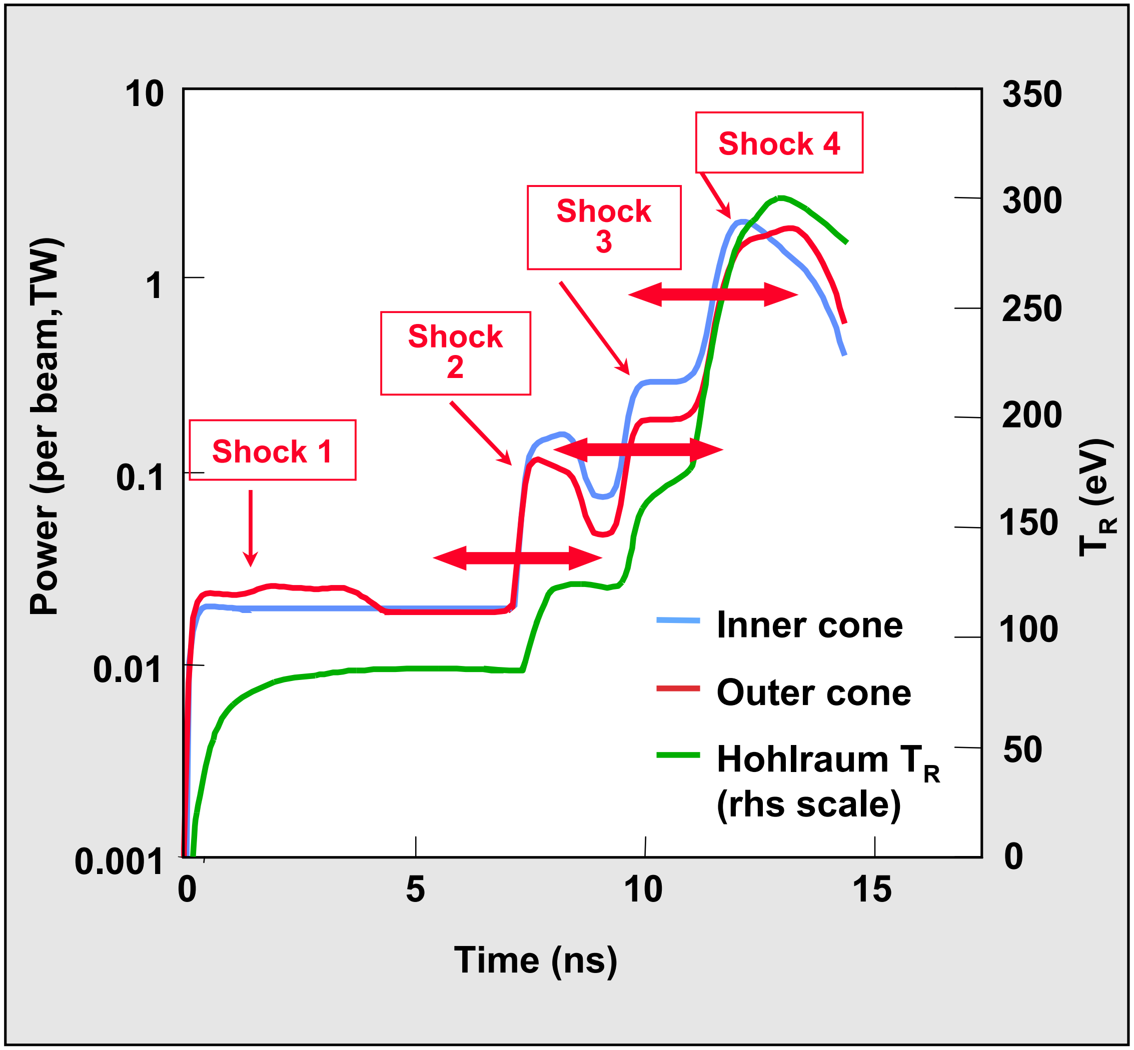
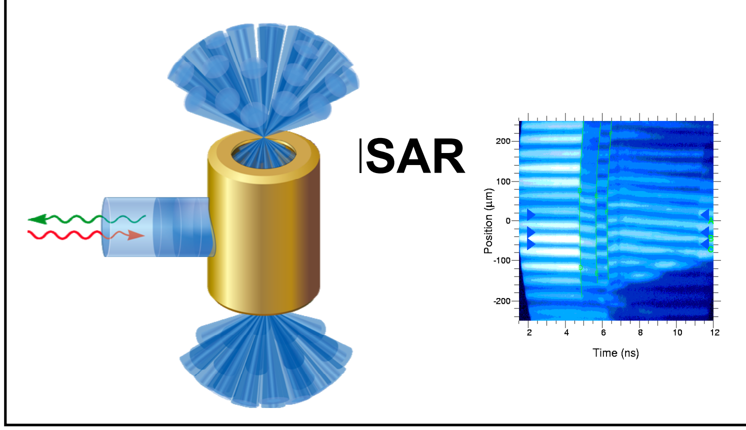
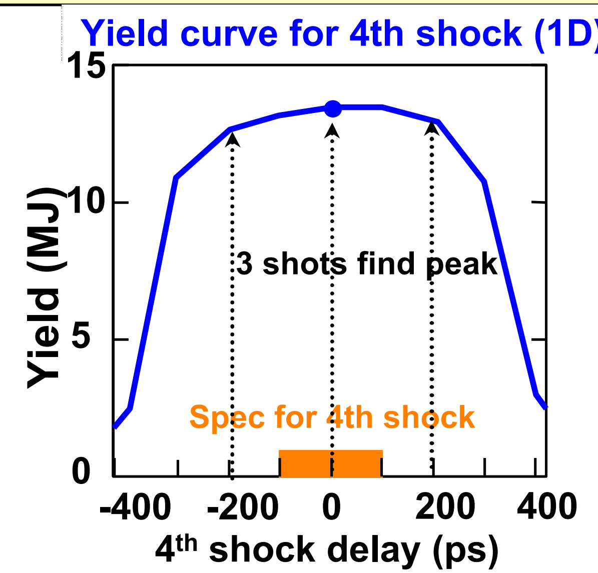


Planar geometry for first 3 shock



Implosions for 4th shock



Requirements: 50 ps on first 3 shocks
100 ps on 4th shock

NIF planar direct-drive experiment activated VISAR and demonstrated steady shock

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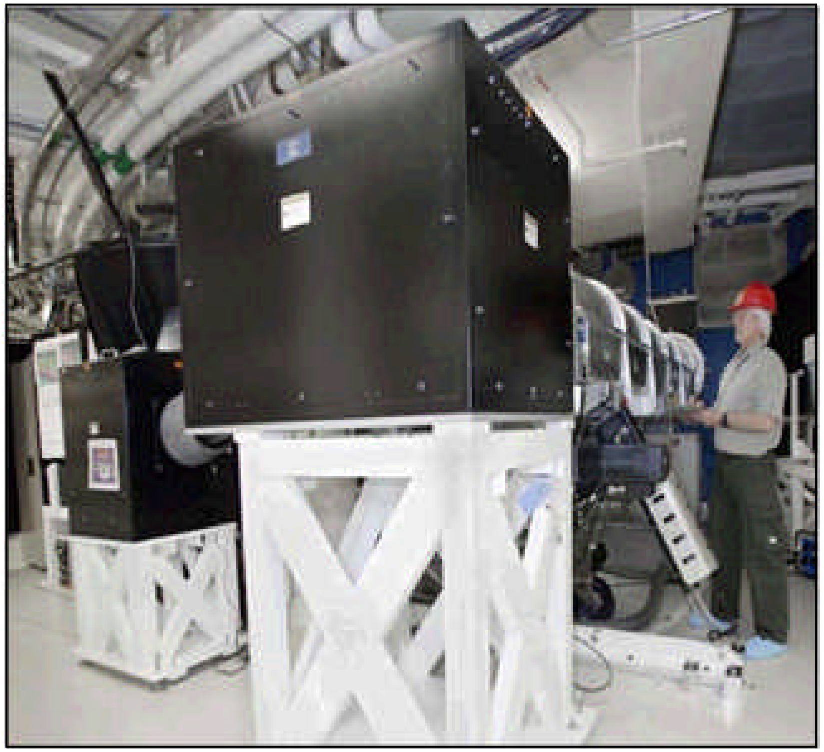
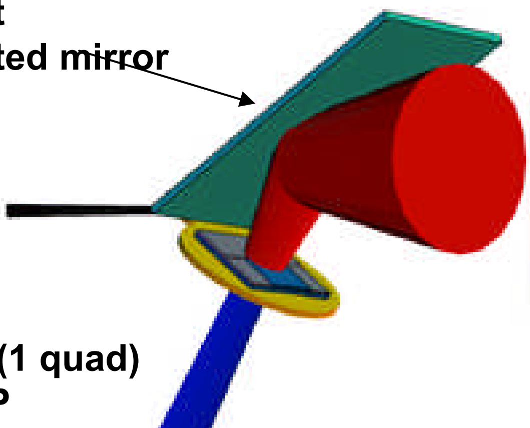
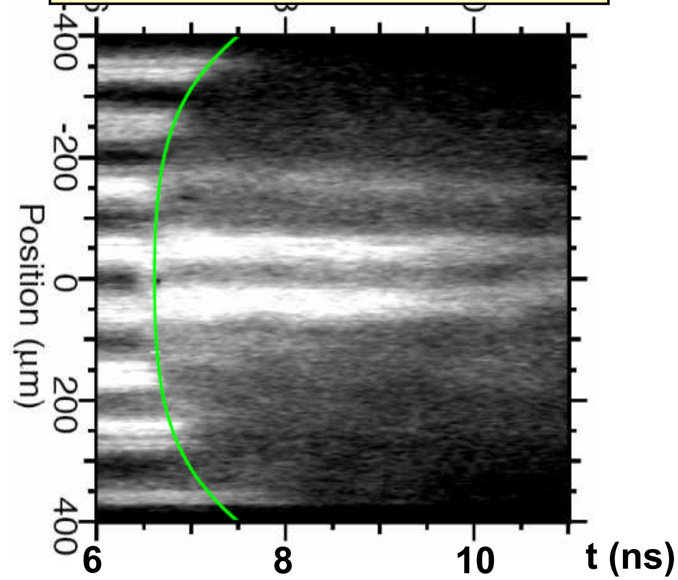


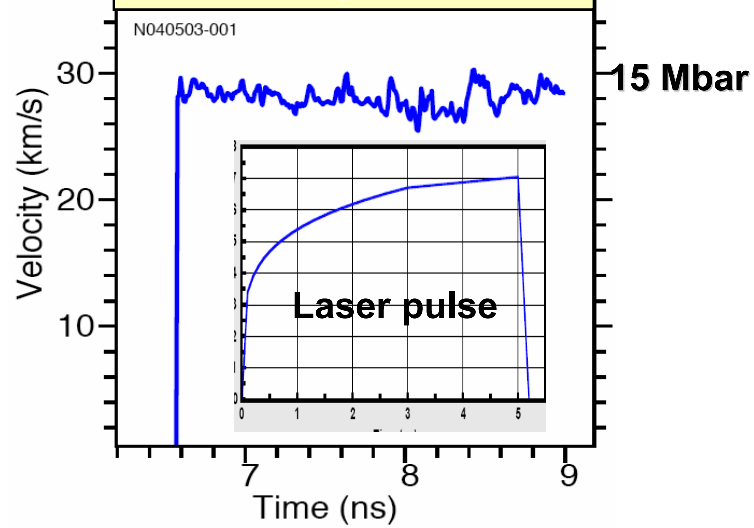
Normal incidence drive



VISAR streaked data



Shock speed steady to 3%



FY2009-10 Conceptual Ignition Campaigns

The National Ignition Facility

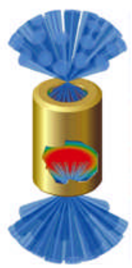
Jan 2009 | **July 2009** | **Apr 2010** | **June 2010**

192 beams Scale 0.7 tuning (~ 350 kJ)

192 beams Scale 1 tuning (up to 1 MJ)

First Look: 96 beams
- Reactivate optical and x-ray diagnostics
- Check 300 eV, LPI, Time-integ. symmetry
- Test tuning techniques

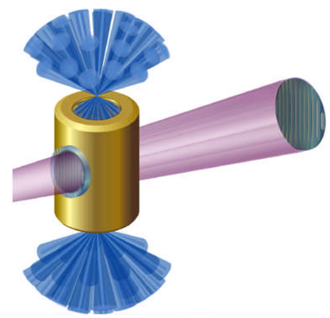
Energetics
- Confirm 300 eV
  - Dante
  - Bang time
  - Time integ symmetry

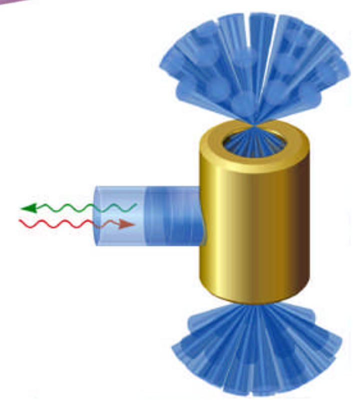


DT Cryo implosion
- Activate Ignition Diagnostics
- Test cryo capsule

Ablator Performance
- Morphology

Ablator Tuning
- Burn-thru





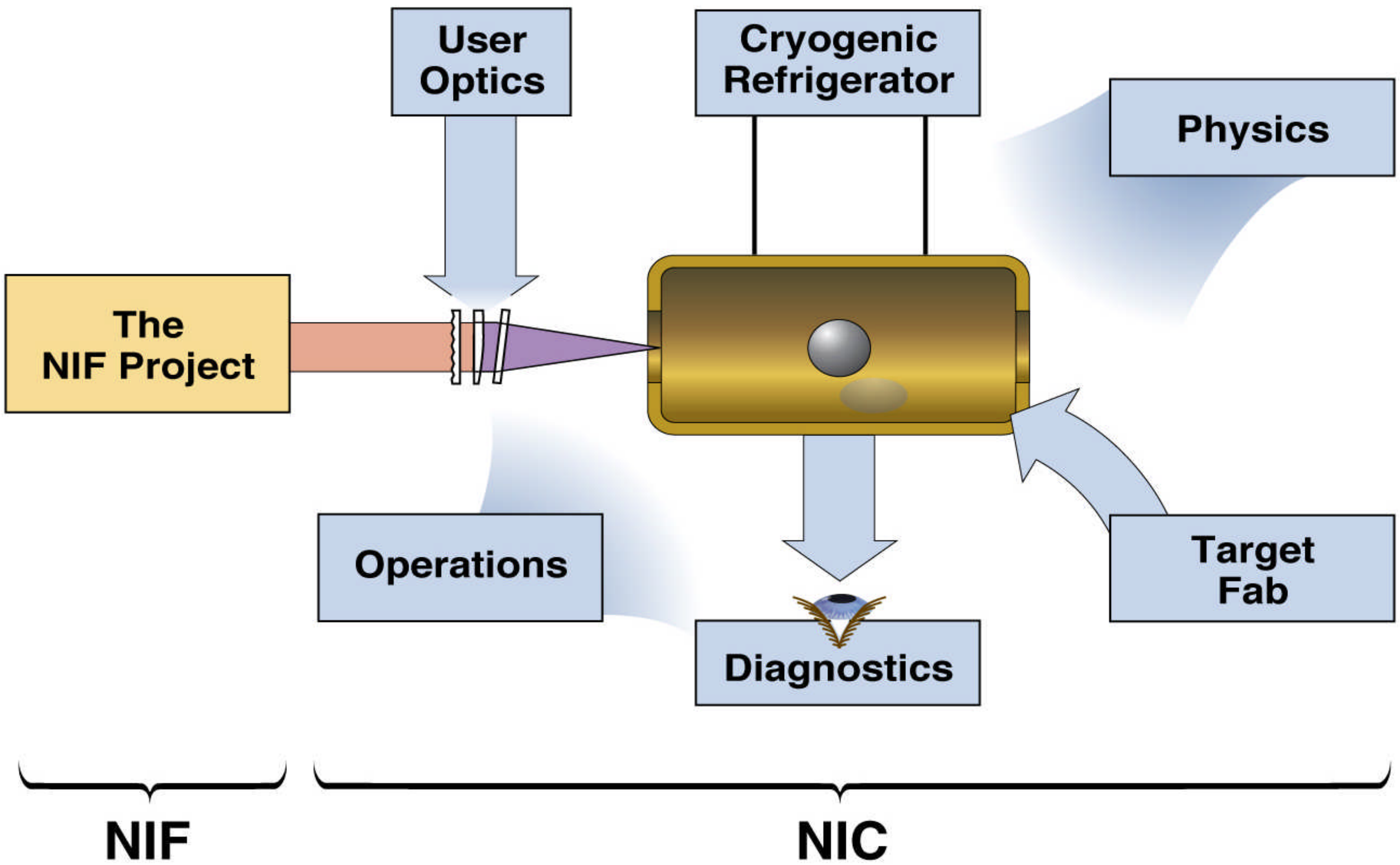
Symmetry Tuning
- Symcaps, Re-emits, Thinshells, Fballs,

Shock Timing
- Hemi Cryo targets

Symmetry
- Symcaps

Ignition Attempt at 1 MJ

The National Ignition Campaign (NIC)



We have demonstrated target fabrication at the component level

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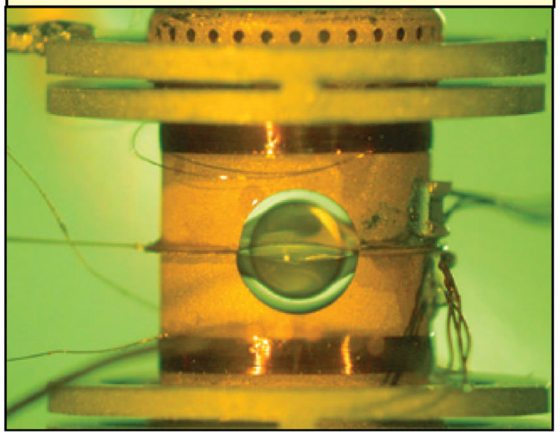
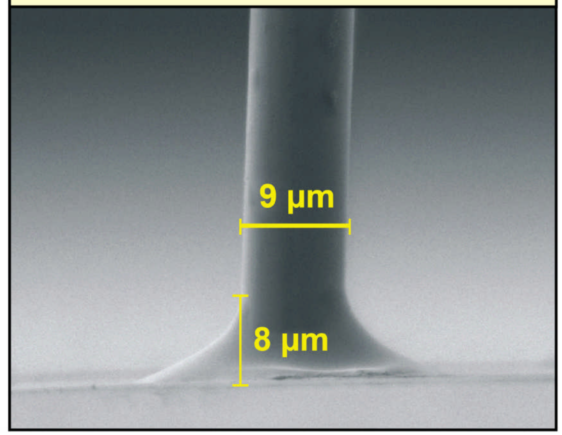
Cryogenic hohlraum

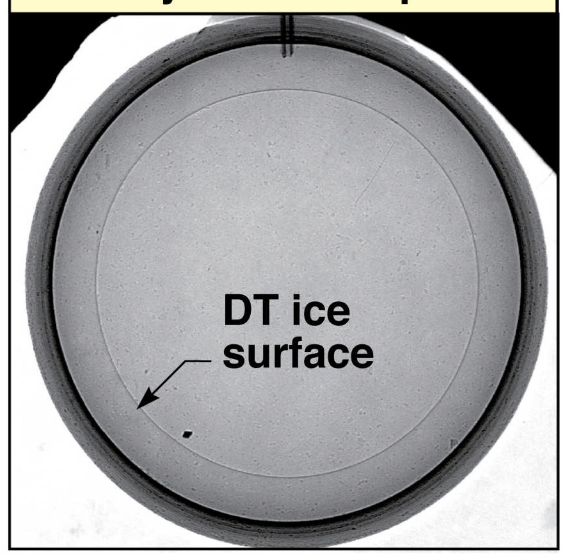


Micro-machined fill tube



Polished Be capsule

DT layer in Be capsule



Polished Be and Diamond capsules are approaching NIF ignition surface finish requirements

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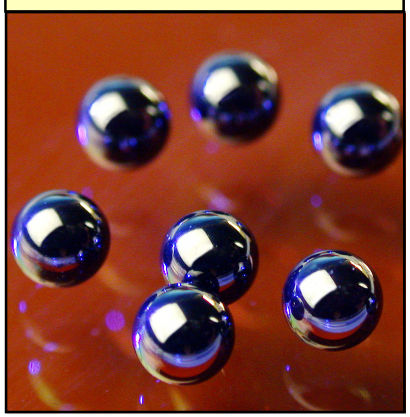
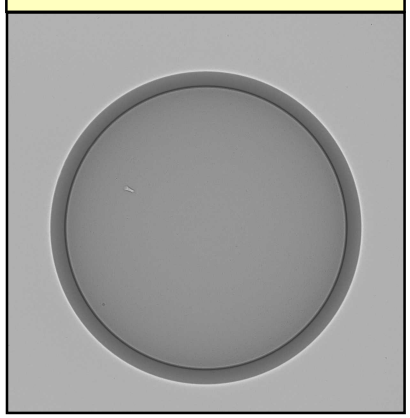
Unpolished and polished Be shells

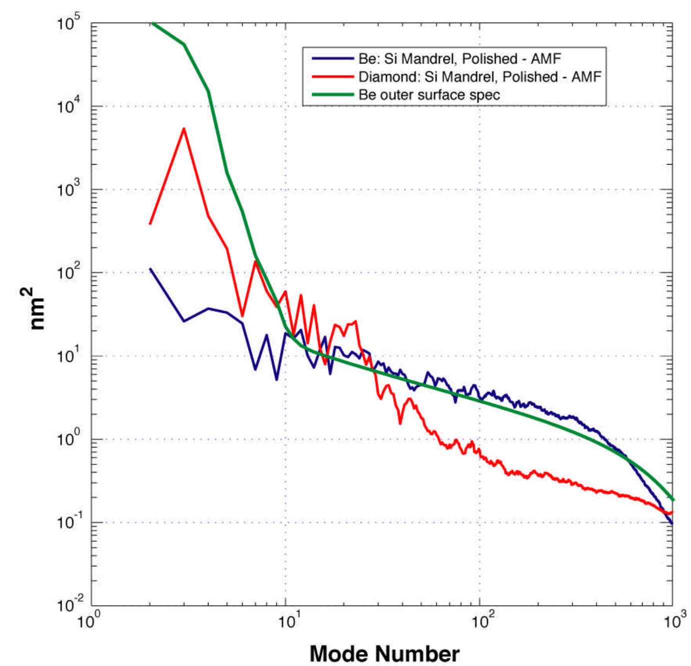
Polished diamond shells



Radiograph of diamond shell



PSD specs and results for Be and Diamond capsules



RMS for modes 2 - 1000
Be: 41 nm Diamond: 86 nm

Diamond shells are produced in collaboration with the Fraunhofer Institute for Applied Solid State Physics, Christoph Wild and Eckhard Woerner

Key fabrication capabilities for fill-tubes are being developed and demonstrated

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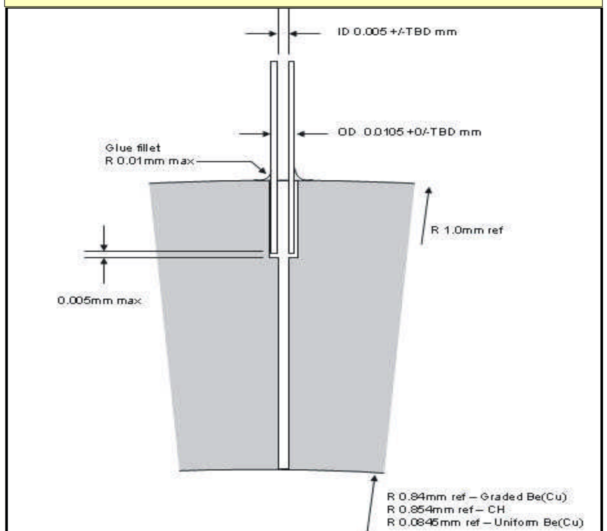
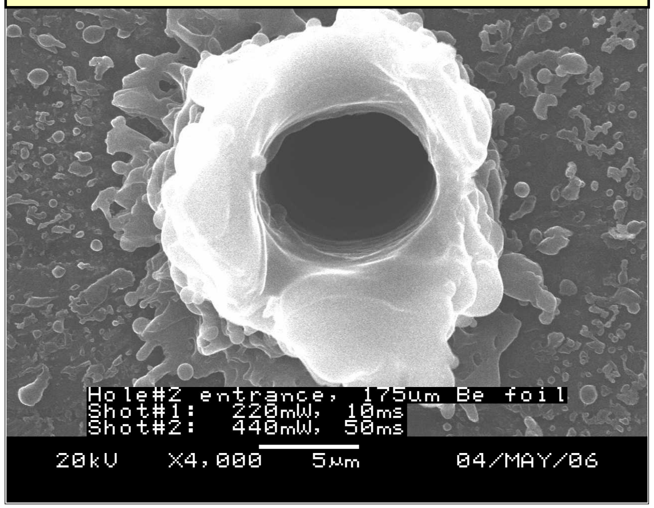
NIF fill tube specification

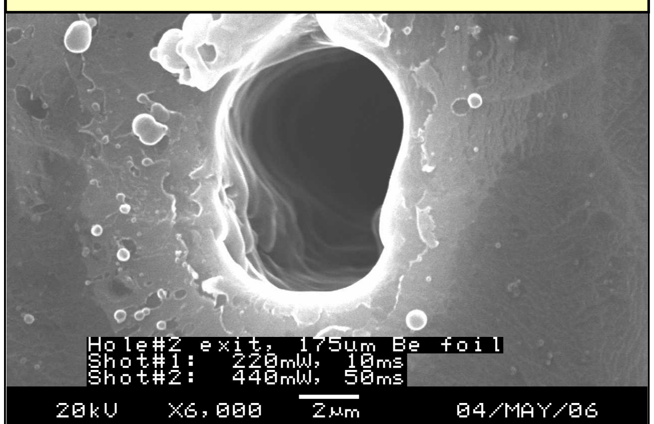


5 μm ID glass tube bonded to a NIF capsule for fuel loading

Entrance Hole

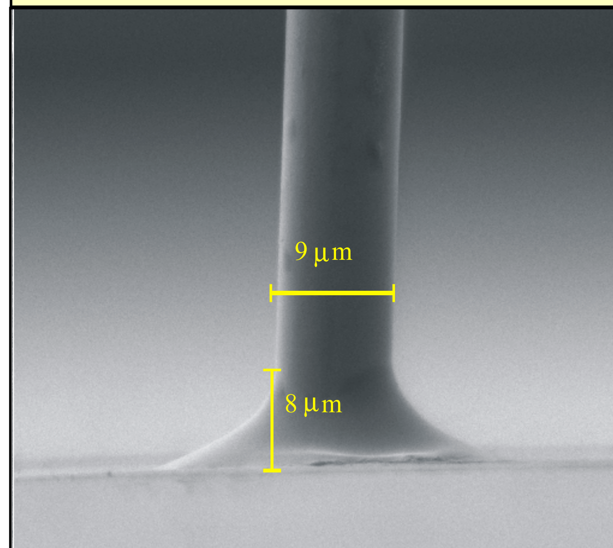


Exit Hole



Hole very close to requirements

NIF fill-tube bond



Bond joint meets NIF mass defect spec of 2.5 ng of adhesive

Advanced Radiographic Capability (ARC) using kJ-class short pulse NIF beams being developed

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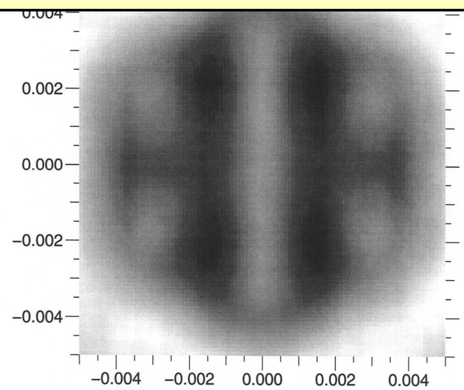
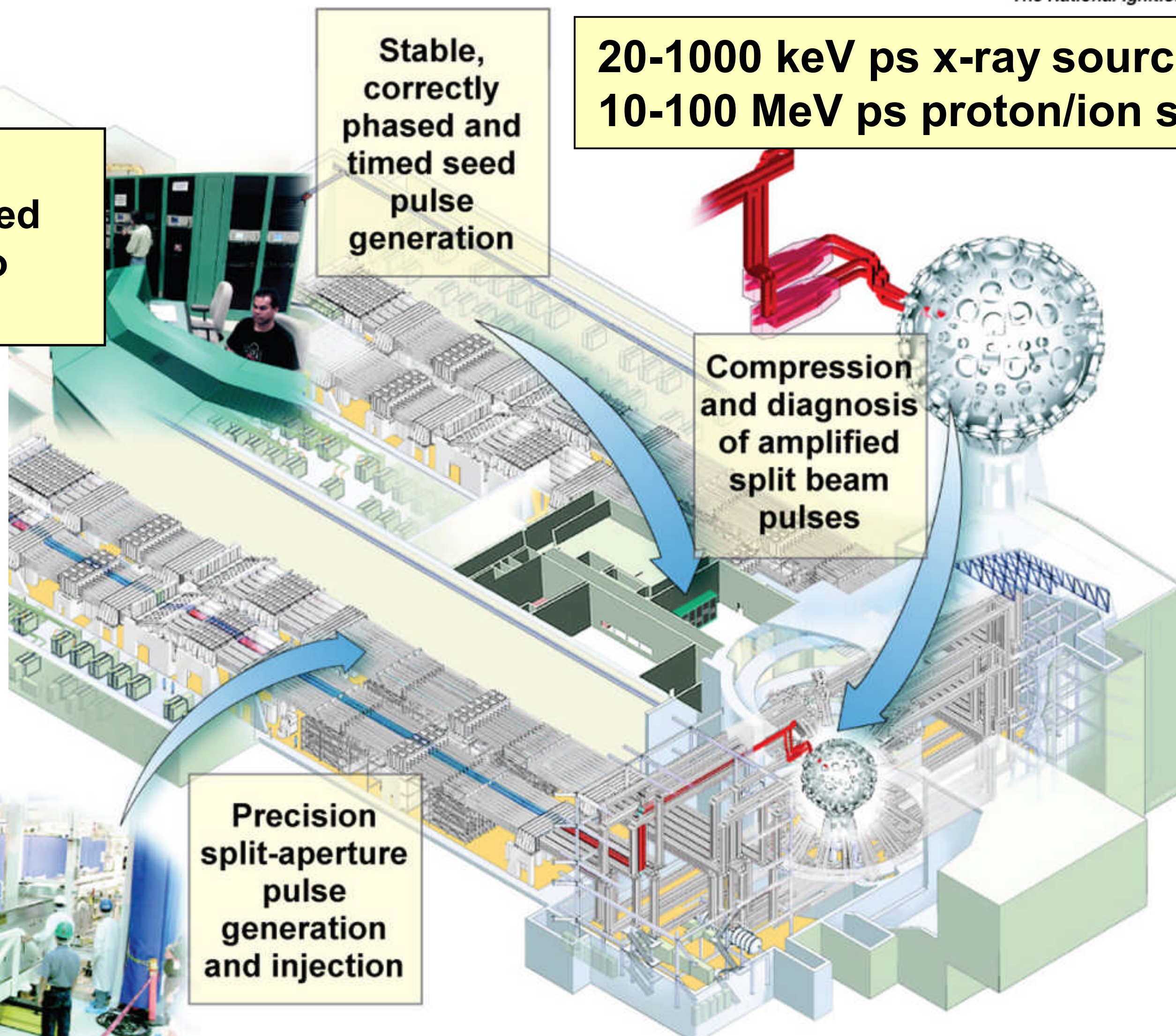
20-1000 keV ps x-ray sources
10-100 MeV ps proton/ion sources

Simulated 90 keV radiograph of imploded non-symmetric cryo capsule



100 µm



Stable, correctly phased and timed seed pulse generation

Compression and diagnosis of amplified split beam pulses

Precision split-aperture pulse generation and injection

NIF could eventually support fast ignition capability

First bundle tested

- Meets all performance requirements
- Over 2 MJ equivalent in the UV

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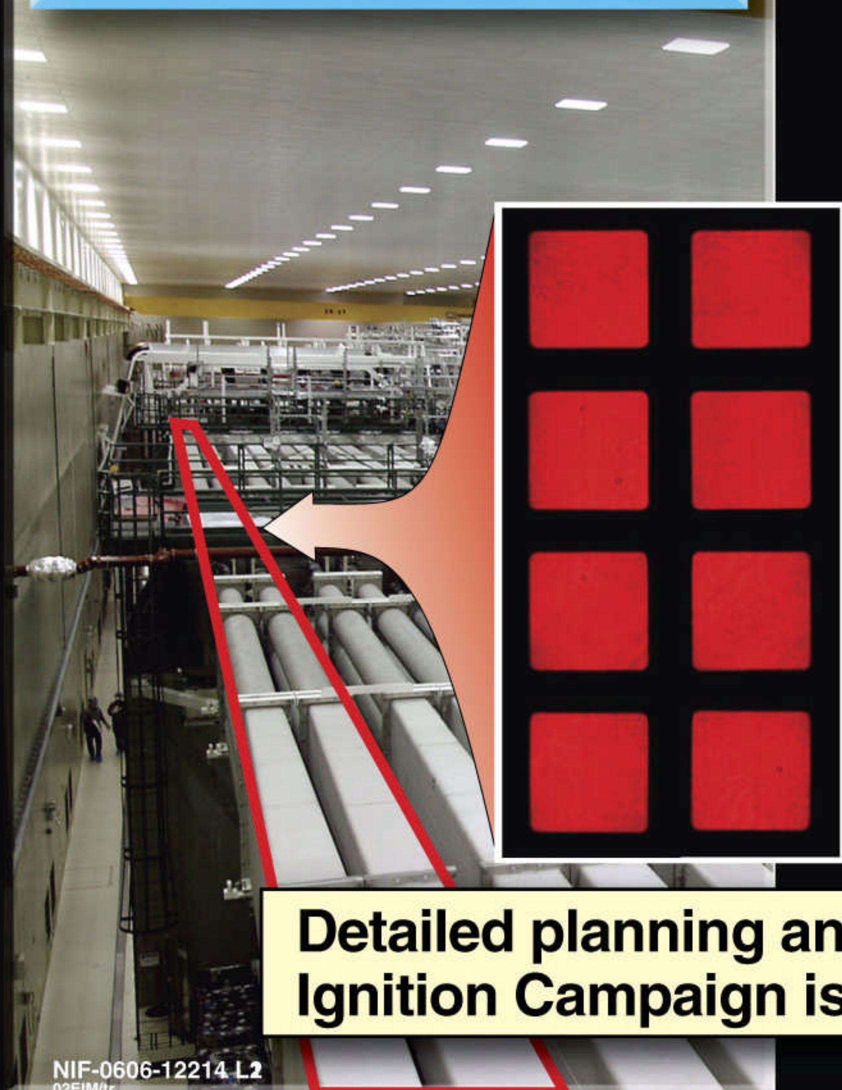
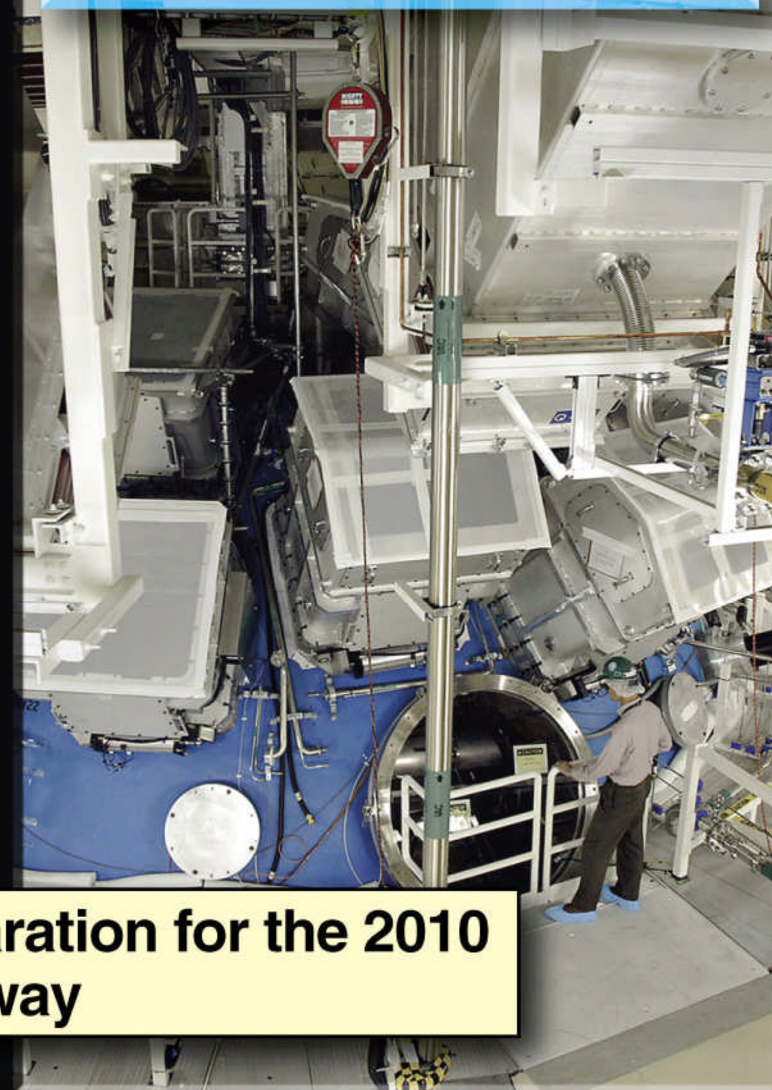
First experiments completed with one quad of beams





Detailed planning and preparation for the 2010 Ignition Campaign is underway

NIF-0606-12214 L2
02EIM/tr

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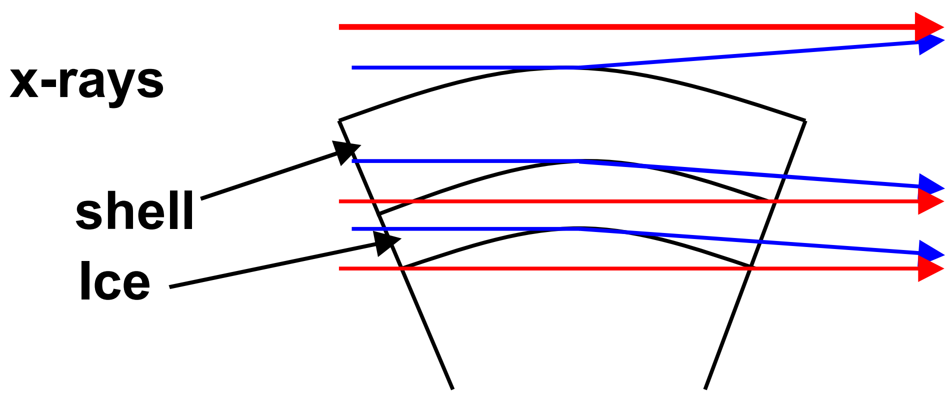
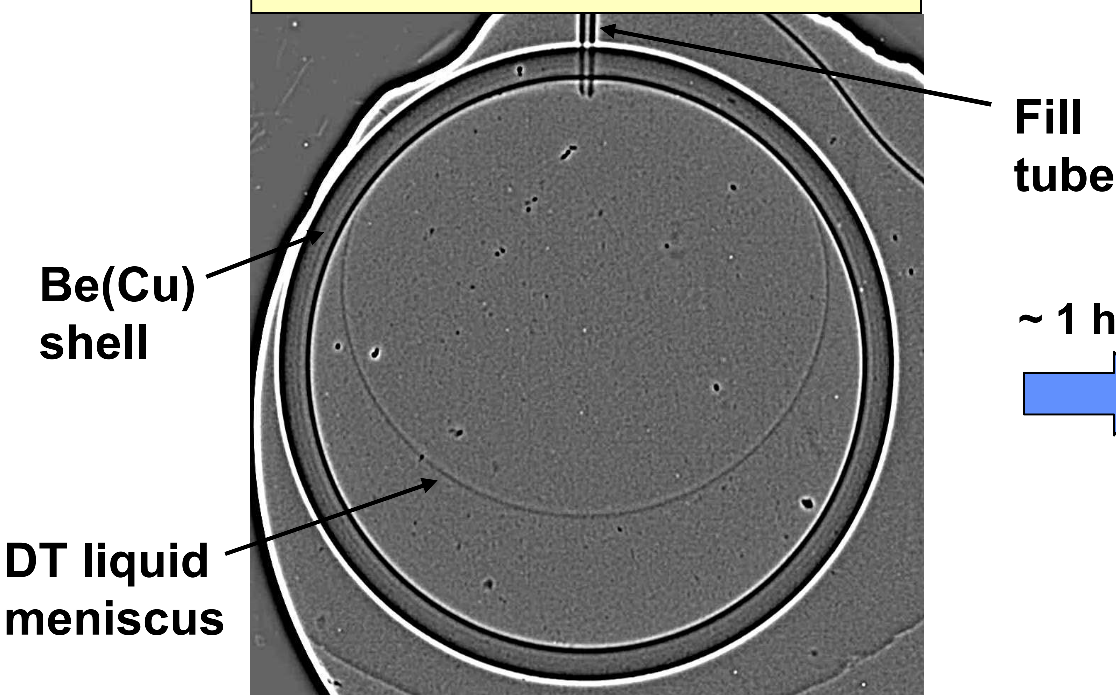
The DT fuel layer in optically opaque beryllium is characterized with x-ray refraction



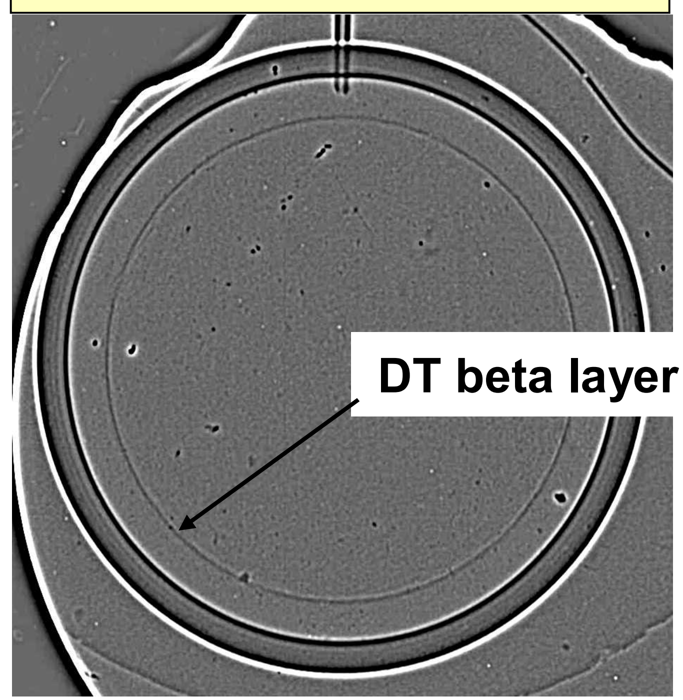
- Rays tangent to surface are slightly deflected
- Other rays are very nearly un-deflected
- This method is many times more sensitive than absorption

Point projection radiograph image



~ 1 hour

Point projection radiograph image



Once the shell is filled we must create a smooth ice layer

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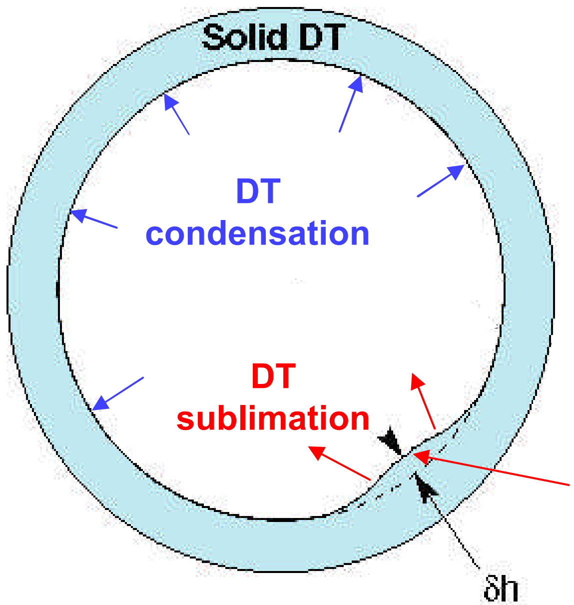
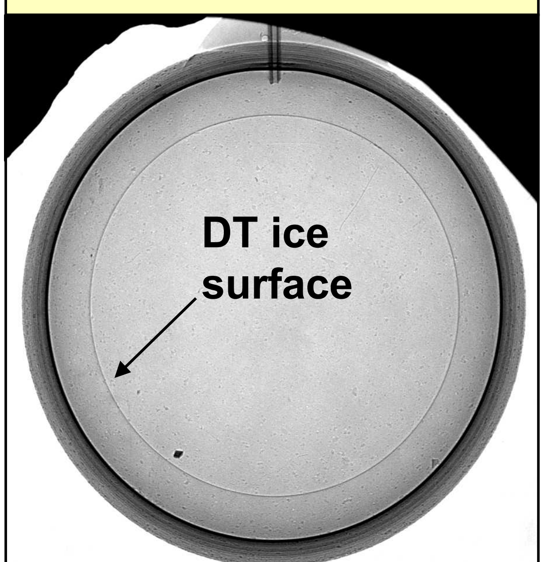


Beta-layering* causes the bump height to decrease as DT sublimes from the warmer region (due to beta-decay of tritium) and re-deposits on colder surfaces

* *J. K. Hoffer and L. R. Foreman, PRL **60**, 1310 (1988)*

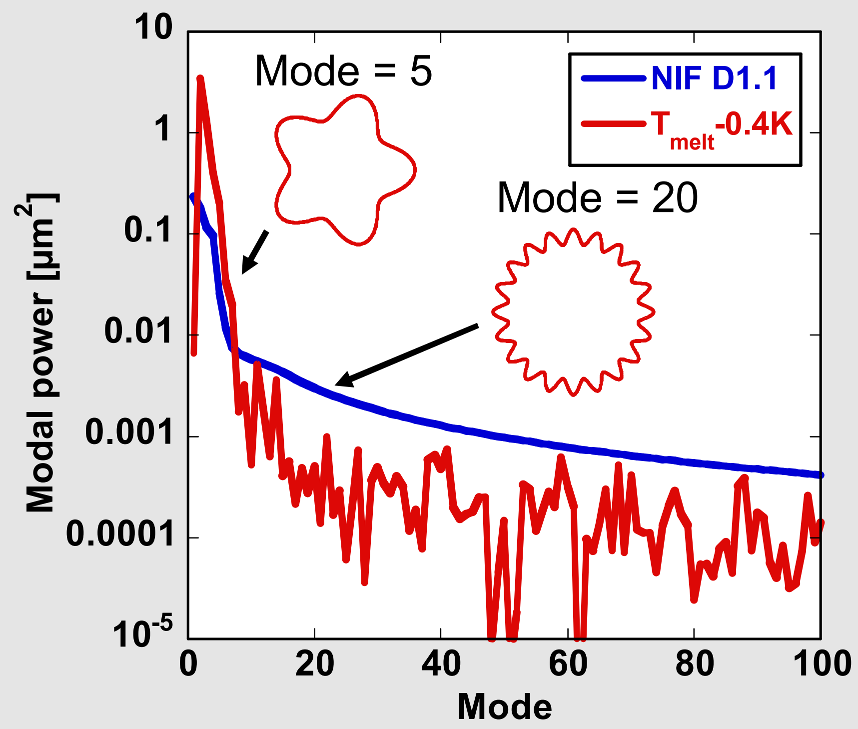
Smooth DT layer in a Be shell



Layer analysis

X-ray phase contrast image

Mode spectrum



X-ray phase contrast has sufficient accuracy for ice characterization

DT layers in Be at 0.3 mg/cc meet the NIF smoothness standard for modes ≥ 7

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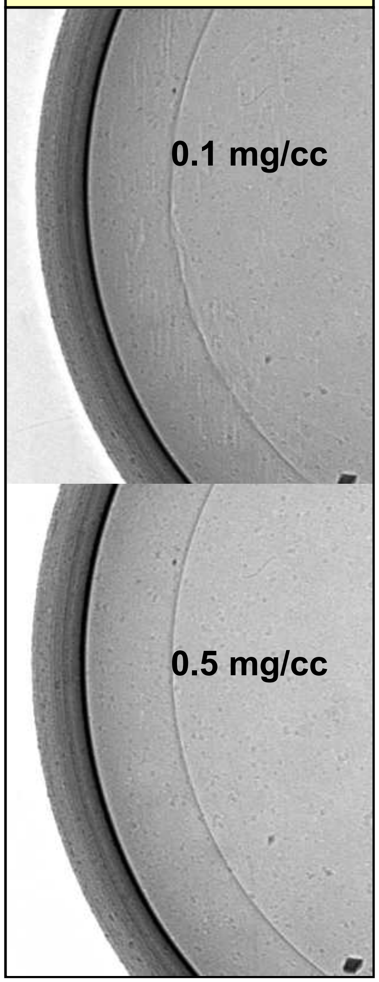
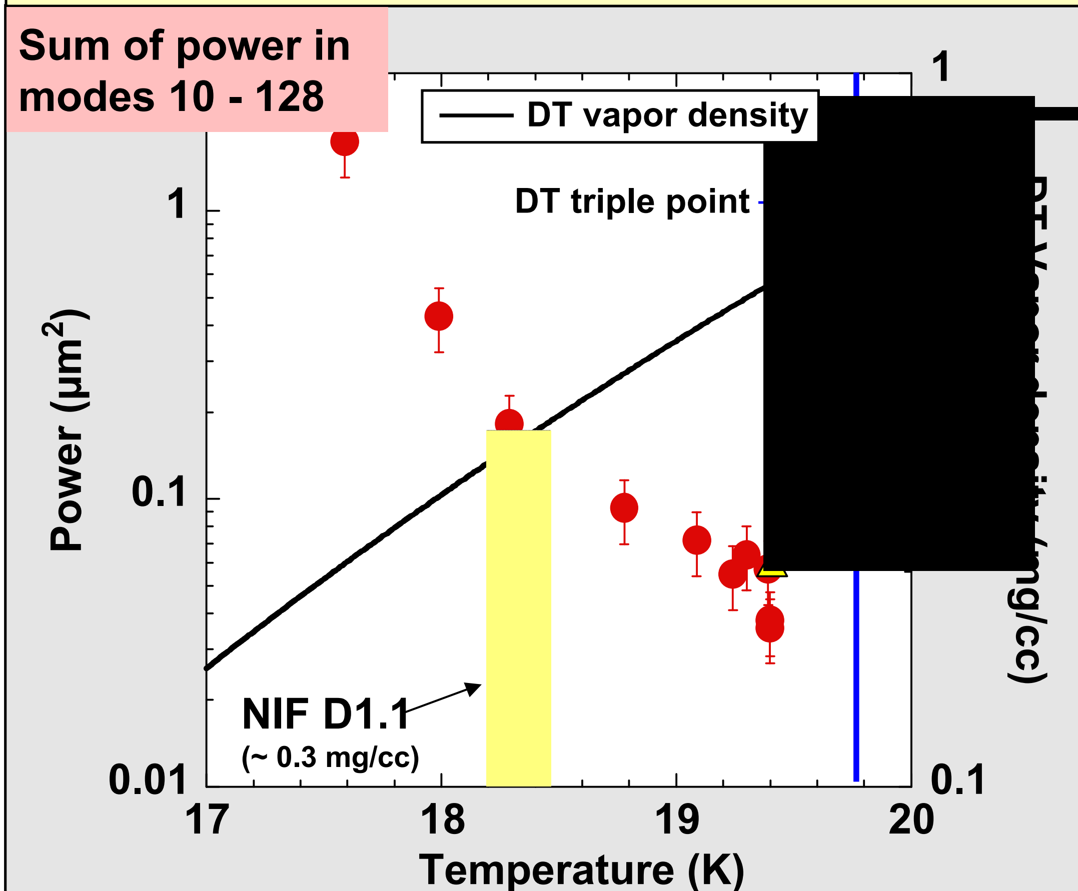
DT layers in a Be shell



The ice layer roughens as the temperature decreases below the triple point



Optical shadowgraphy of a DT layer in a transparent shell

Modes 1-3 add about 2 μm to the RMS value. The cause of this power is the large glue joint

Fabrication of multi-layer U:Au cocktail hohlraums is under development

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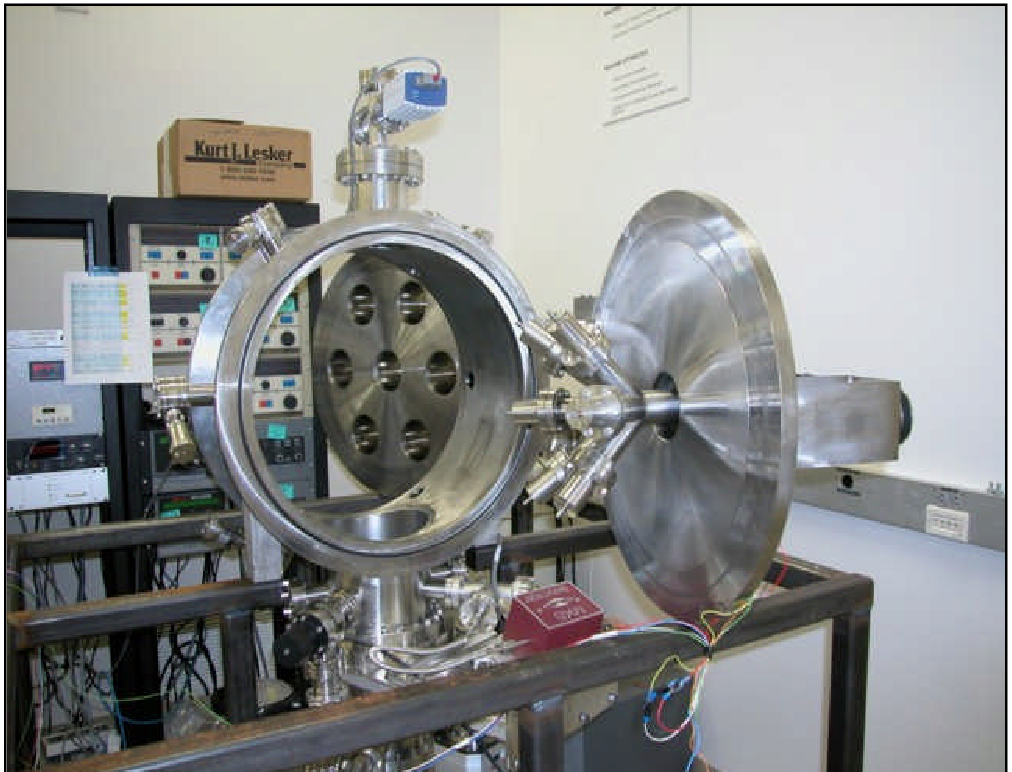
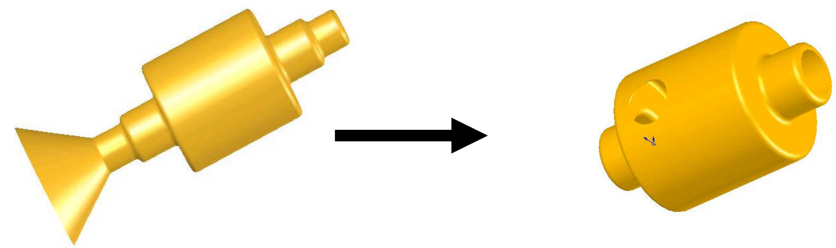


Cocktail coater



Coat mandrel

Remove mandrel

Multi-layer U:Au cylinder

- Multi-gun sputter system for multilayer deposition
- First-order optimization of the coating parameters is well underway
  - Residual stress in the layers
  - Oxidation of U

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Diagnostics for Ignition Campaigns

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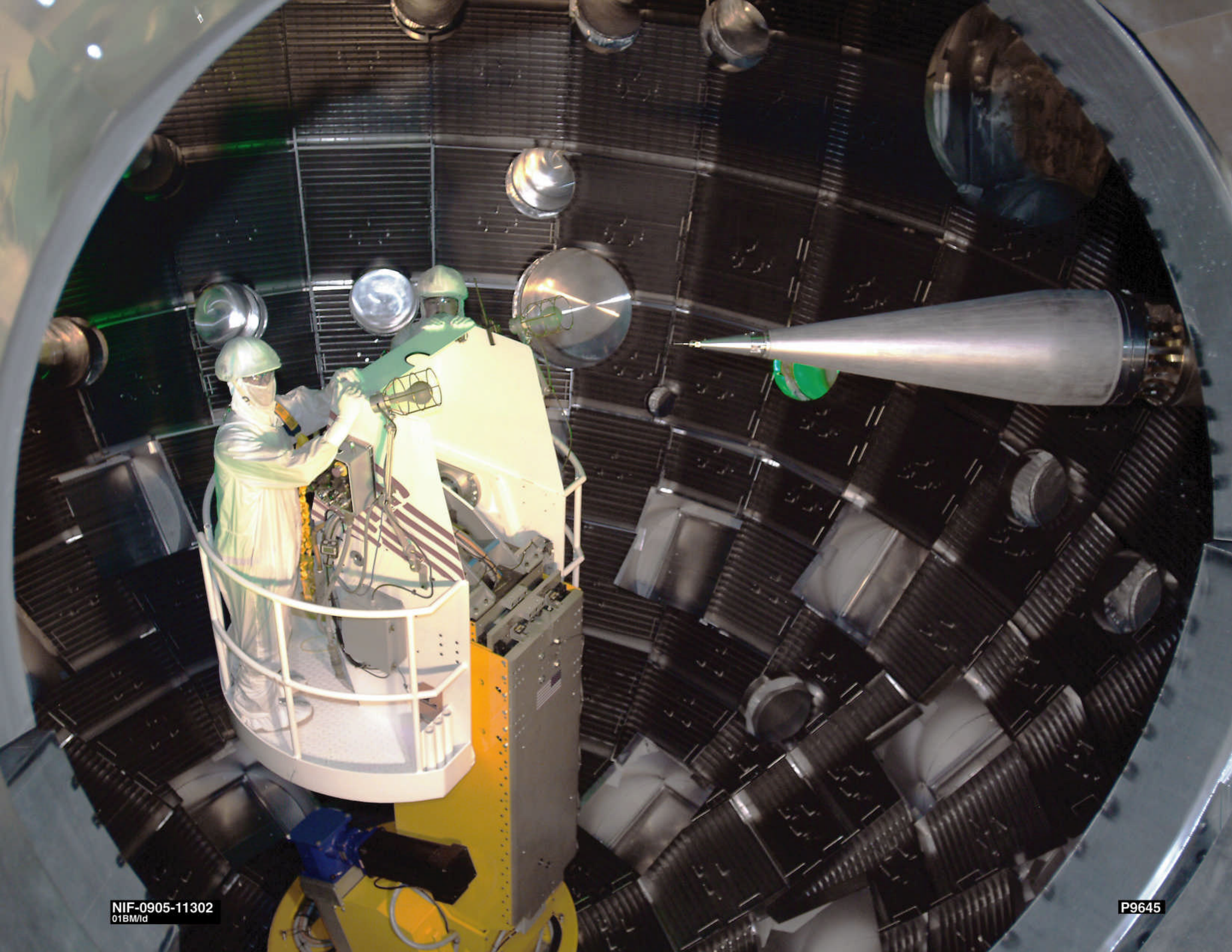
	Energetics	Symmetry	Ablator	Shock Timing	Implosions
Optical	•Full Aperture Backscatter (2) •Near Backscatter Imager (2)			•VISAR interferometer •SOP	
X-ray	•Soft x-ray Power (Dante) •Gated soft x-ray imager •Hard x-ray spectrometer (Filter Fluorescer) •X-ray Bangtime	•Gated x-ray imaging (2) •X-ray Bangtime	•Soft x-ray streaked imaging •Gated x-ray imaging •CR39? •Radchem?	•Streaked x-ray imaging •X-ray Bangtime	•Core x-ray imaging •X-ray Bangtime •ARC Compton backlighting
Nuclear	•DD yield by nToF			•DT yield	•DT yield •Neutron time of flight spectroscopy • γ-ray detector (bangtime) •Magnetic Recoil Spectrometer •Neutron imaging •C12 Activation


NIF-0905-11302
01BM/ld
P9645

The Precision Diagnostic Station is used to validate the Final Optics configuration and operations strategy

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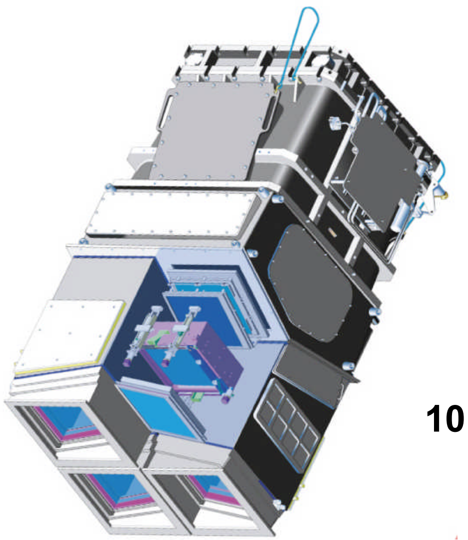

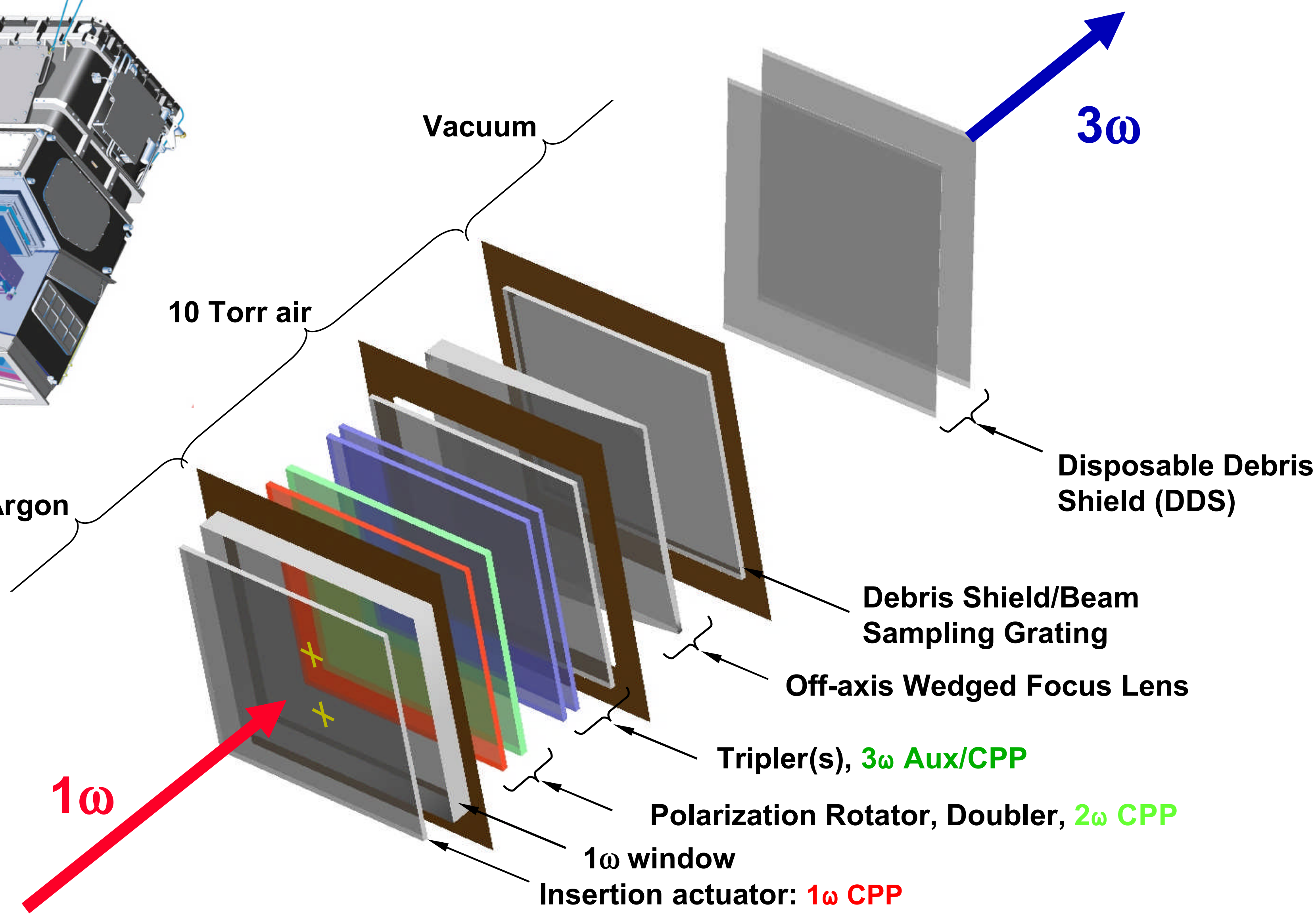

PDS demonstrated the 1 MJ ignition point design energy, power, pulse shape & beam smoothing simultaneously

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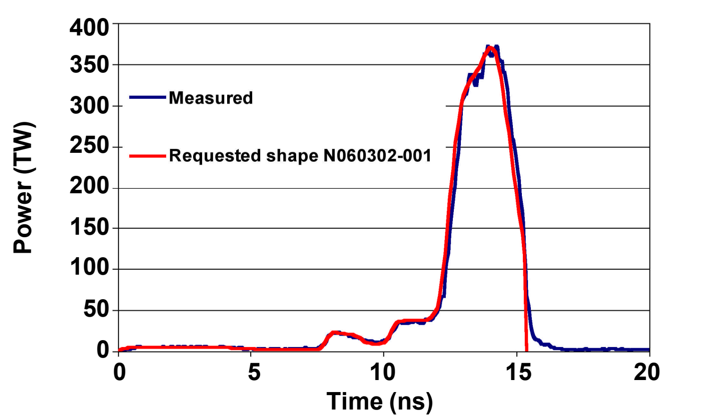
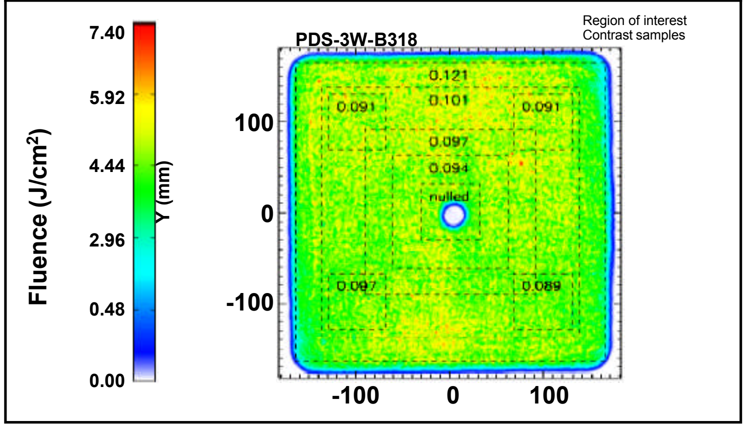
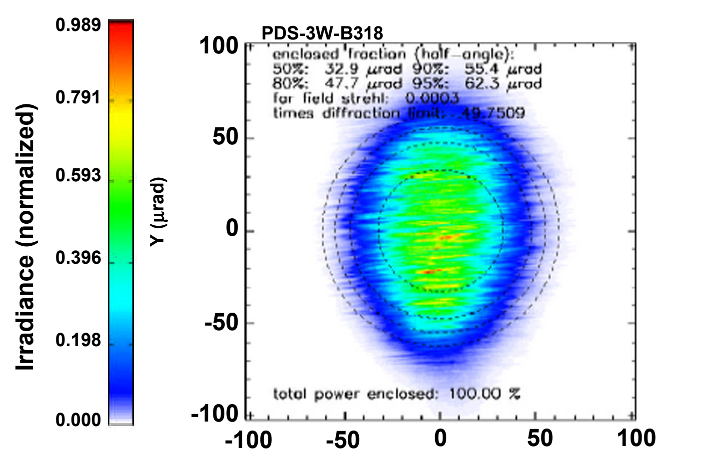
3ω Pulse Shape (374 TW)



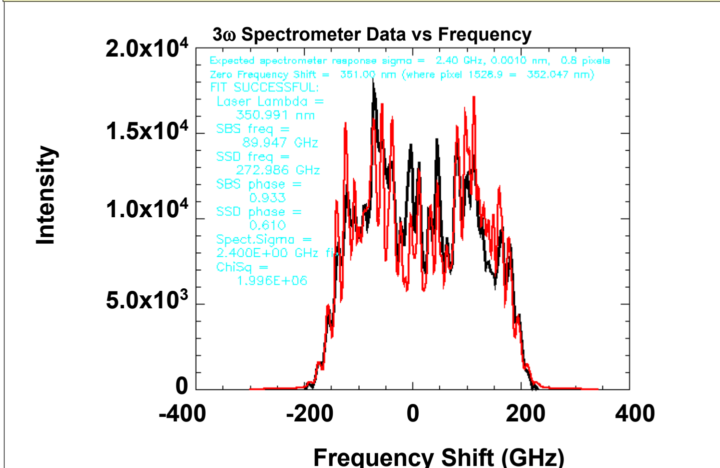
3ω Near Field Profile (CR = 10.1%)



3ω Focal Spot (0.95 x 0.5 mm²)



3ω SSD Bandwidth (270 GHz)

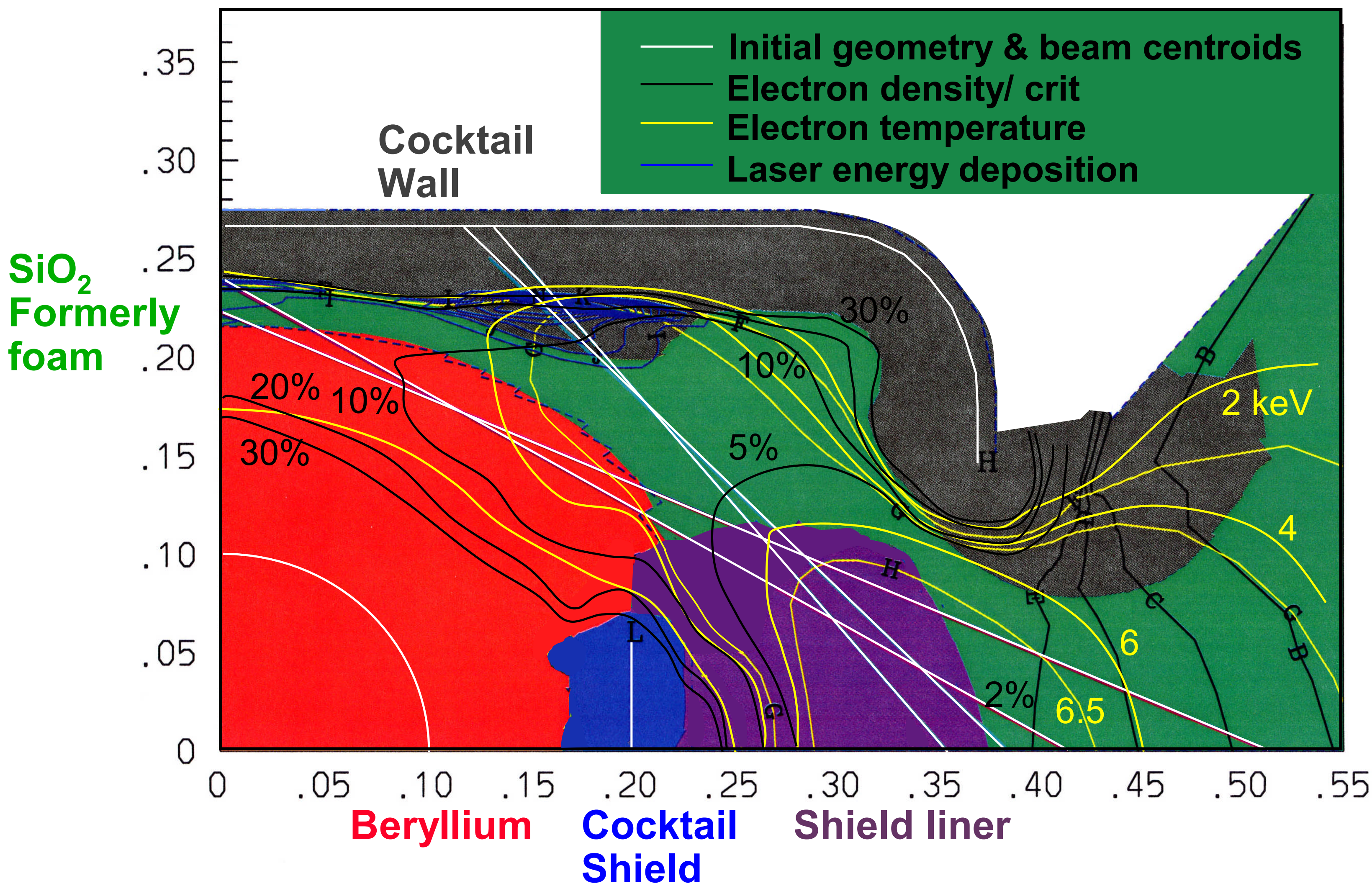


FY06 laser performance campaign summary: NIC ignition point design shot series

Description			Beam energy and power			Beam smoothing		
Shot series	Pulse shape	Pulse length (ns)	3ω energy per beam (J)	3ω energy full NIF (MJ)	Peak power (TW/beam)	CPP (mm) FWHM	Rotated pol.	SSD (GHz, 3ω)
1 MJ ignition design	ignition	15.4	5208	1.0	1.85	.95 x .50	yes	270
Results	ignition	15.4	5390	1.03	1.9	.95 x .50	yes	270
1.8 MJ ignition design	ignition	20.4	9375	1.8	2.6	1.3 x 1.2	yes	90
Results	ignition	20.4	9572	1.84	2.6	1.3 x 1.2	yes	100

On a beamline basis, NIF has now met or exceeded the primary criteria and functional requirements, and the more challenging NIC requirements

Hohlraum conditions at peak power



Re-emission sphere provides earliest time-dependent symmetry measurement

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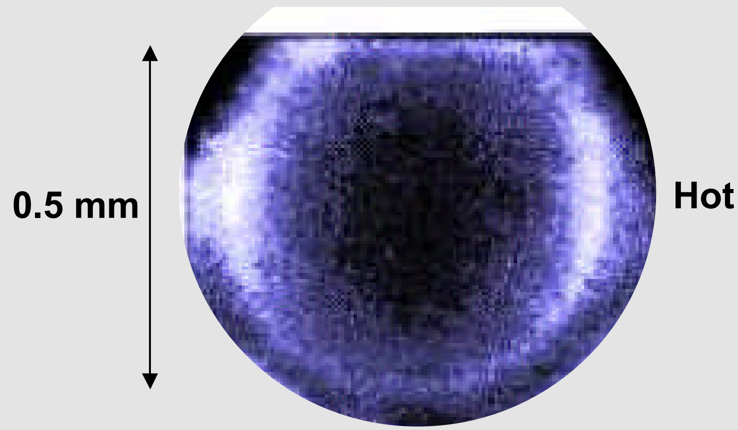
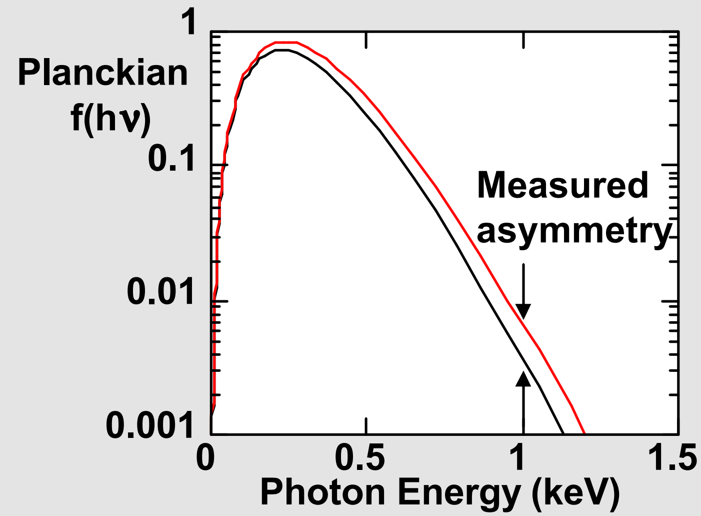
2 keV gated x-ray pinhole camera image of Bi re-emission sphere



Re-emission sphere displays intentional P_2 hohlraum asymmetry

Comparison of re-emission spectra for ΔTr = 5% @ Tr = 80 eV



Flux asymmetry magnified by factor $h\nu/4kT_r$ in tail of Planckian

For NIF, Re-emission sphere will measure instantaneous P_n for first 2-3 ns with 3% accuracy

Delamater, Phys. Rev. E (1996); Magelssen, Phys. Rev. E (1998)

Foamballs and thinshells provide time-dependent symmetry measurement through middle of pulse

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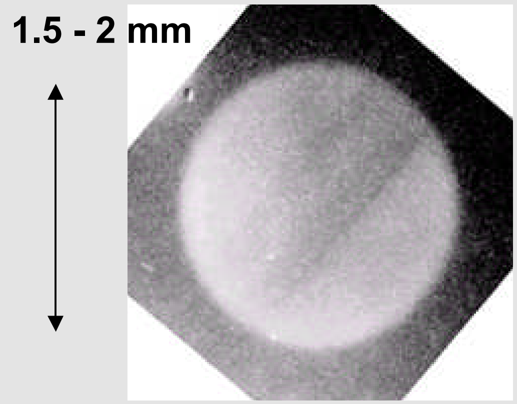
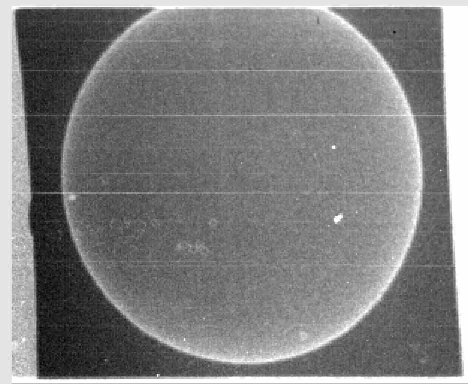
4 keV gated x-ray pinhole radiograph of 0.1 g/cc SiO_2 foamball



$$a_n(t) = -1/2\int_0^t vP_n(t')dt'$$

5 keV gated x-ray pinhole radiograph of 10 μm CH(Ge) shell



$$a_n(t) = -\int_0^t vP_n(t')dt'$$

A fractional ablation pressure asymmetry P_n leads to spatial distortion a_n in limb after it travels a distance $v\Delta t$

For NIF, Foamball will measure $P_2(t)$ swings to 5% and 2.5% per ns in foot and peak of pulse

For NIF, Thinshell will measure weighted average of $P_{n>2}$ to 0.5% and 0.2% in foot and peak of pulse

Amendt, Phys Rev .Lett. (1996); Phys Plasmas (1997)

Pollaine, Phys Plasmas (2001); Bennett, Phys. Rev. lett. (2002); Vesey, Phys. Rev. Lett. (2003)

Symmetry measurement techniques agree with each other and are reproducible

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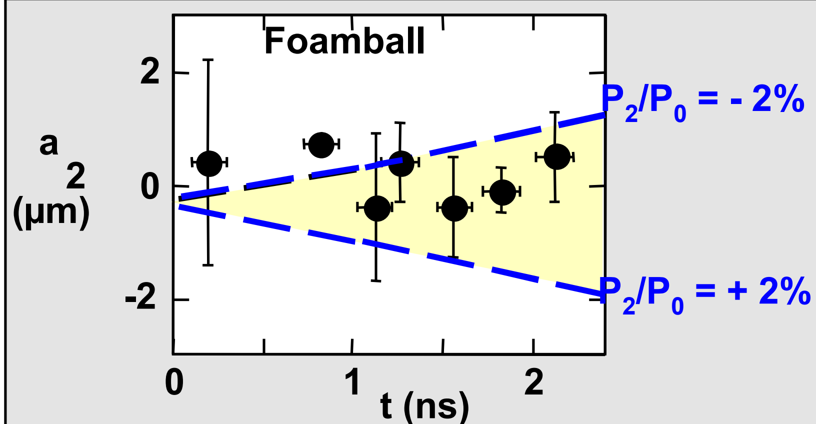
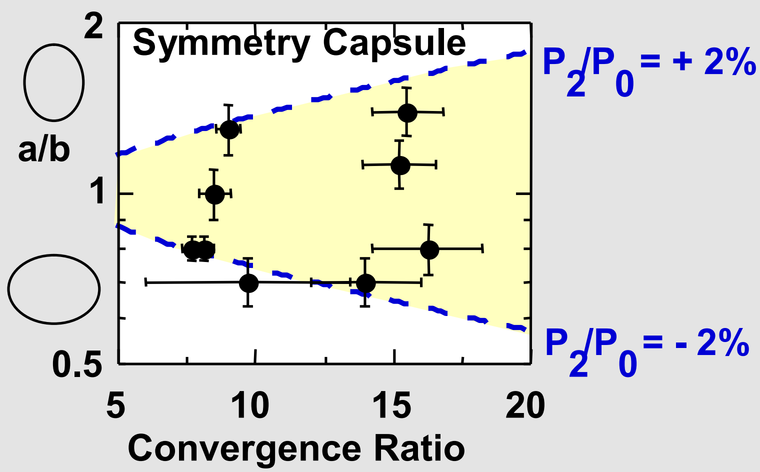
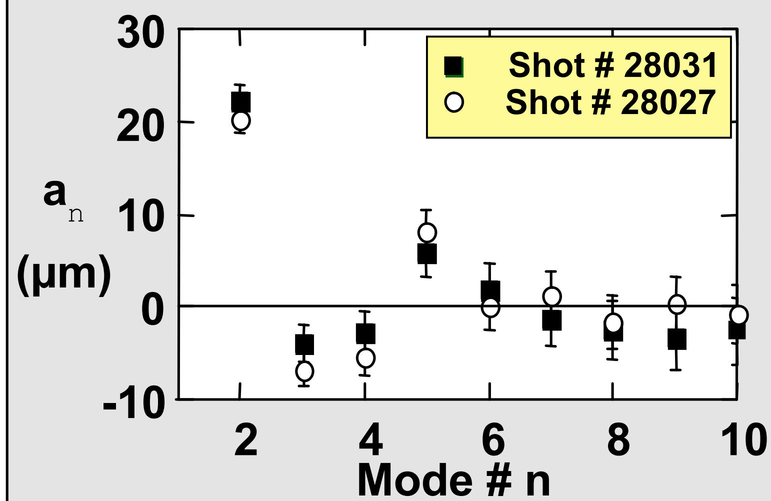
Comparison of foamball and symmetry capsule data





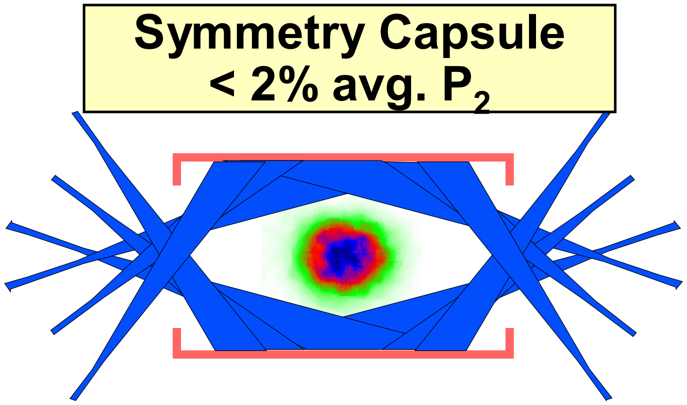
Agreement between inferred asymmetry

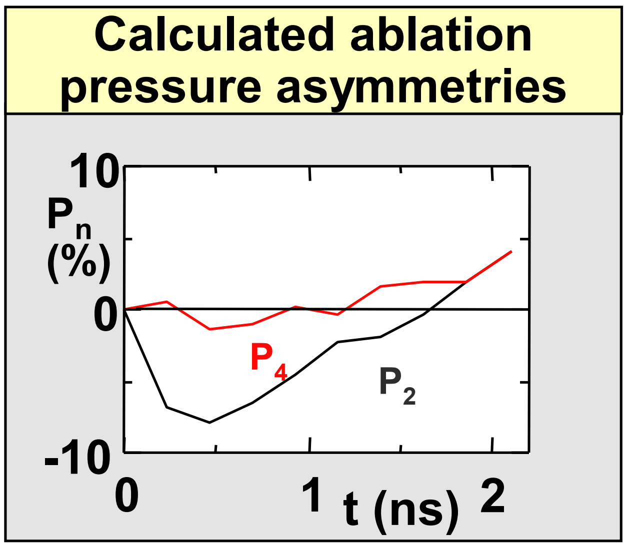
Comparison of thinshell distortion on 2 shots

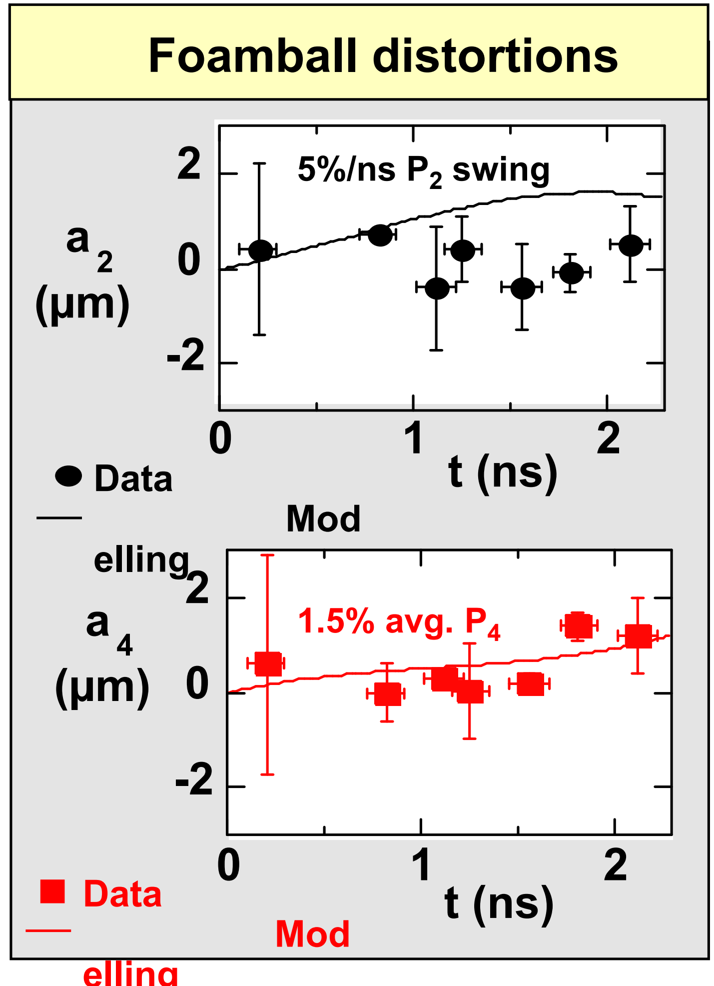


Reproducible to few micron level required for ignition

NIF-like multiple ring vacuum hohlraums at Omega have produced symmetric drive







R. Turner, P. Amendt et al., Phys. Plasmas (2003)

- P_2 and P_4 control and measurement to 5%/ns, better than required for NIF
- Independent cone pulse-shaping also demonstrated on Nova and Omega

R. Turner, P. Amendt et al., Phys. Plasmas (2001)

Current asymmetry diagnostic accuracies just meet NIF 2010 1 MJ ignition requirements

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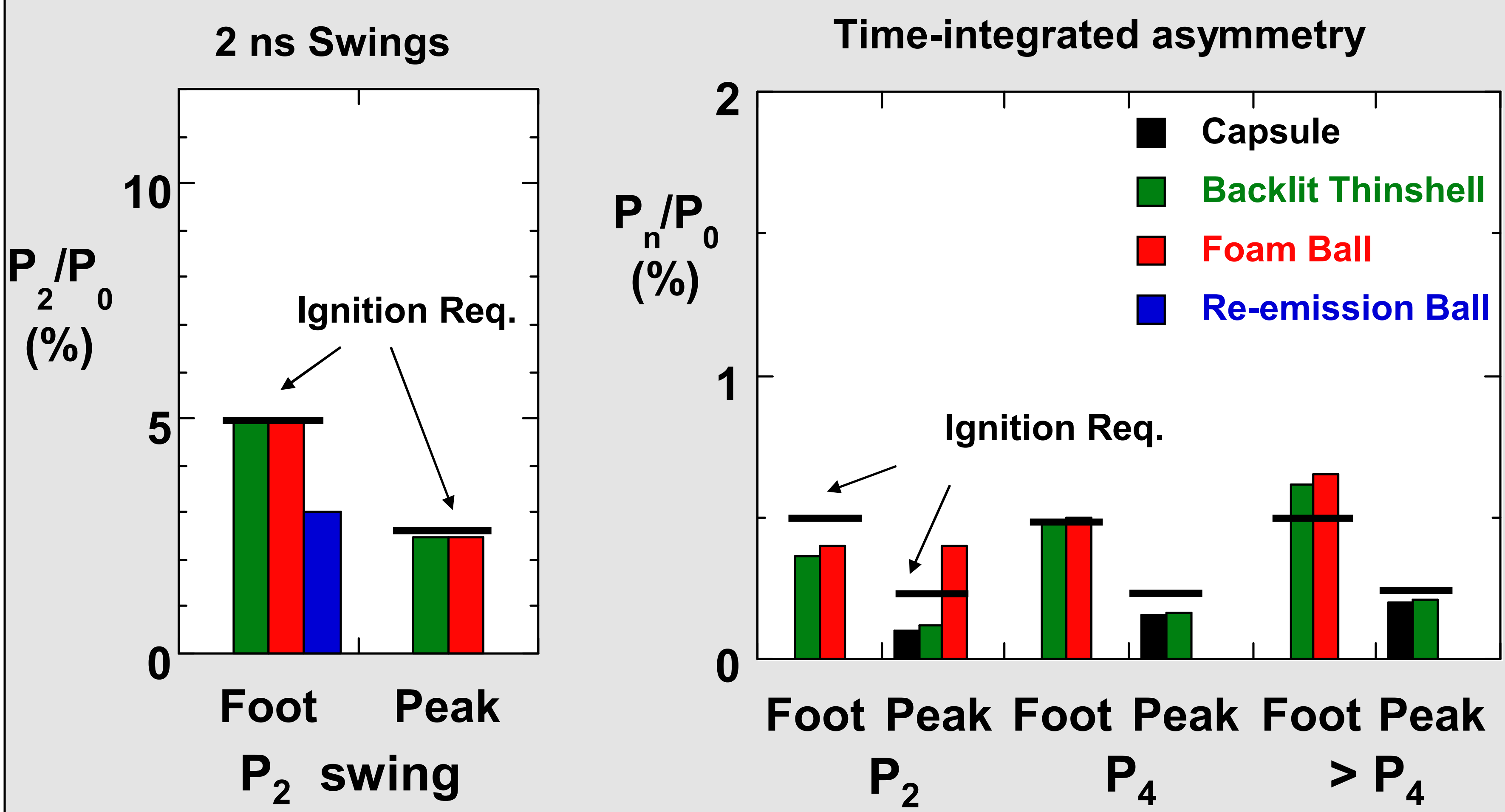
NIF symmetry diagnostic accuracy extrapolated from Nova and Omega results compared to ignition requirements



NIC tuning designs need to evaluate additional uncertainties due to extrapolating from imperfect surrogacy of techniques

Varying shell thickness symmetry capsules will provide running integral of symmetry history during peak drive

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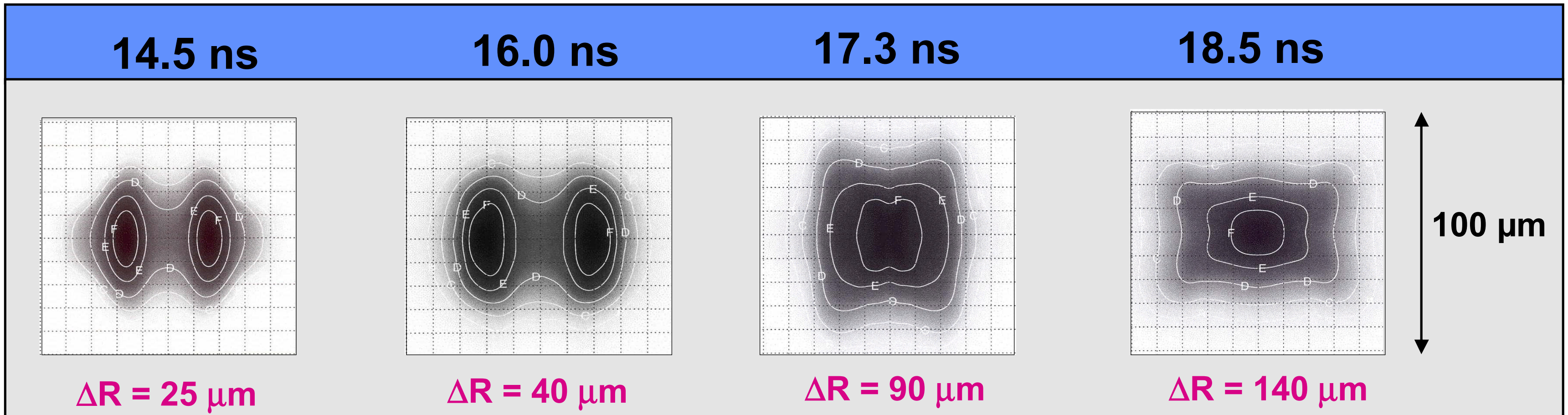
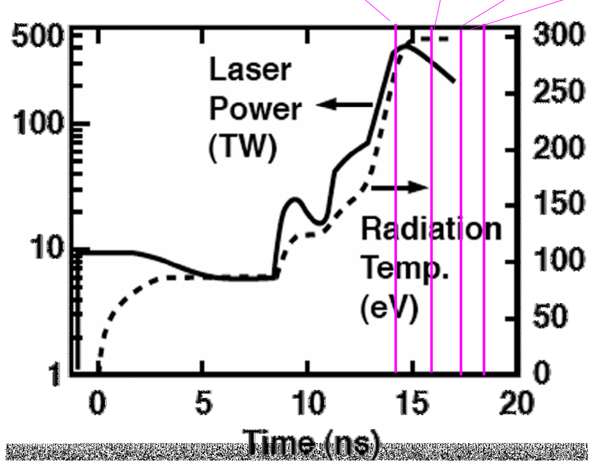
Simulated x-ray core images





A. Hauer, *et. al.*, Rev. Sci. Instrum (1991)

R. Turner, P. Amendt, *et. al.*, Phys Plasmas (2001)